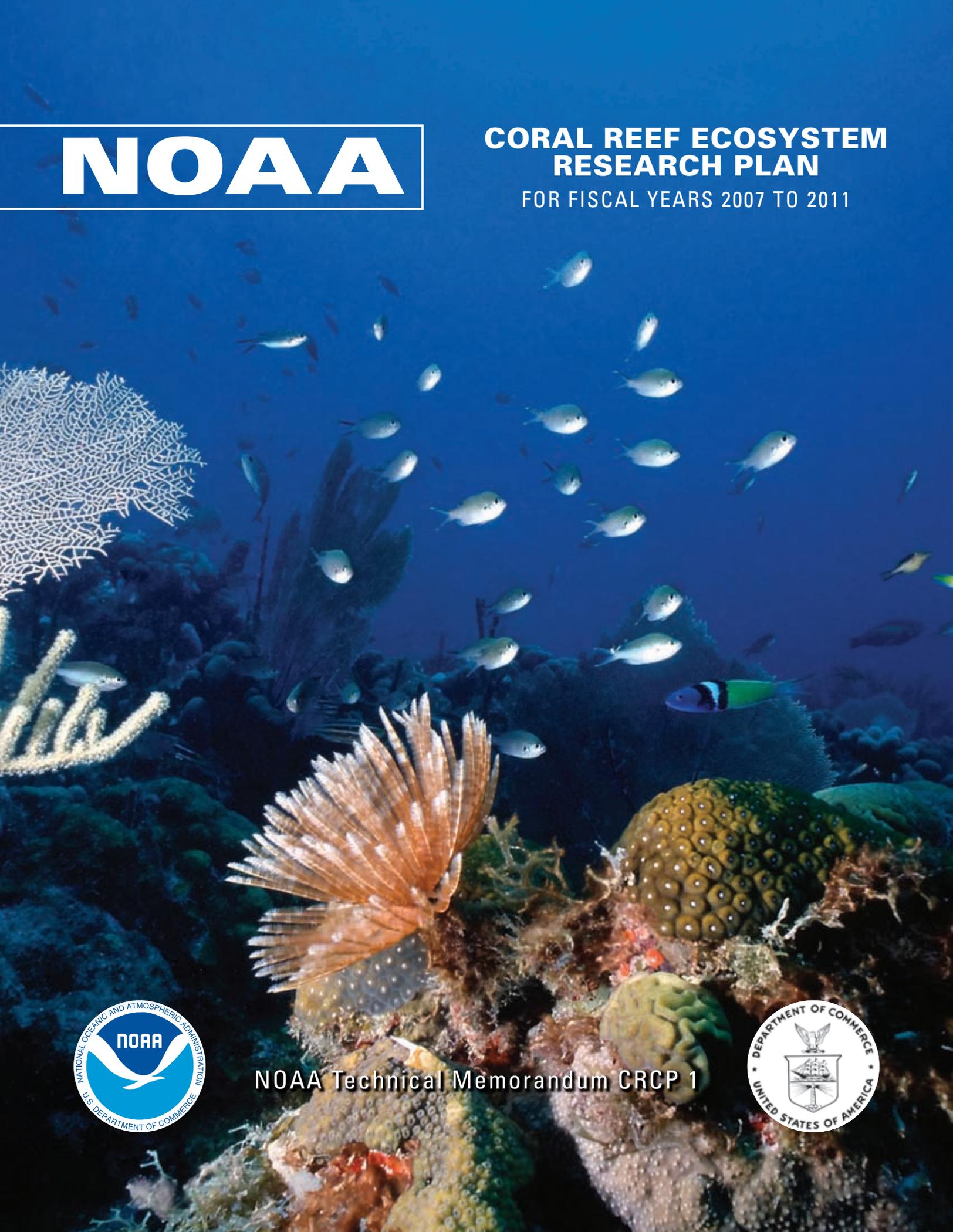


NOAA

CORAL REEF ECOSYSTEM RESEARCH PLAN

FOR FISCAL YEARS 2007 TO 2011



NOAA Technical Memorandum CRCP 1



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NOAA Coral Reef Ecosystem Research Plan for Fiscal Years 2007 to 2011

K.A. Puglise and R. Kelty (eds.)

National Oceanic and Atmospheric Administration

January 2007



NOAA Technical Memorandum CRCP 1



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Acronyms

BMPs	Best management practices
C.F.R.	Code of Federal Regulations
CNMI	Commonwealth of the Northern Mariana Islands
COTS	Crown-of-thorns starfish
CRCA	Coral Reef Conservation Act of 2000
DOI	U.S. Department of the Interior
E.O.	Executive Order
EPA	U.S. Environmental Protection Agency
FGBNMS	Flower Garden Banks National Marine Sanctuary
FKNMS	Florida Keys National Marine Sanctuary
F.R.	Federal Register
FSM	Federated States of Micronesia
FWS	U.S. Fish and Wildlife Service
FY	Fiscal year
GIS	Geographic information system
GPRA	Government Performance and Results Act of 1993
HAPC	Habitat Area of Particular Concern
MCD	Marine Conservation District
MHI	Main Hawaiian Islands
MPA	Marine protected area
NBSAP	National Biodiversity Strategy and Action Plan
NOAA	National Oceanic and Atmospheric Administration
NWHI	Northwestern Hawaiian Islands
NWR	National Wildlife Refuge
PAR	Photosynthetically active radiation
PRIAs	U.S. Pacific Remote Insular Areas
SPAs	Sanctuary Preservation Areas
U.S.C.	United States Code
USCRTF	United States Coral Reef Task Force
USVI	U.S. Virgin Islands
UV	Ultraviolet radiation

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Introduction



Figure 1. School of reef fish at Rapture Reef (French Frigate Shoals, Northwestern Hawaiian Islands). Photo credit: James Watt.

Coral reef ecosystems are highly valued for their biological, ecological, cultural, and economic resources, as well as their aesthetic qualities (Figure 1). Worldwide, coral reef ecosystems provide over \$30 billion in annual goods and services (Cesar et al. 2003) and yet cover less than 1% of the earth's surface. Annual goods and services provided by coral reef ecosystems include renewable and non-renewable resources, coastline protection, increased property values, tourism, and marine natural products.

Within the United States, the economic contribution of coral reef ecosystems has been calculated for Hawaii (Figure 2), southeast Florida, American Samoa, Guam, and the Commonwealth of the Northern Mariana Islands. In the Main Hawaiian Islands, coral reefs were estimated to provide annual economic benefits of over \$360 million, 85% of which was directly attributed to recreation and tourism (Cesar et al. 2002). In the four-county area of southeast Florida (Palm Beach, Broward, Miami-Dade, and Monroe Counties), artificial and natural reefs supported 28.3 million person-days of recreational diving, fishing, and viewing activities and generated approximately \$4.4 billion in local sales, almost \$2 billion in local income, and 71,300 full- and part-time jobs (Johns et al. 2001).

In American Samoa, where tourism is low, the annual economic value was estimated to be \$5 million for coral reef ecosystems and \$1 million for mangrove ecosystems (JacobsGIBB Ltd. 2004).

In the past few decades, competing demands on coral reef ecosystems and increasing threats from both natural and anthropogenic stressors, including fishing, pollution, coastal uses (e.g., land and water development and recreational use), invasive species (Figure 3), climate change, and extreme events (e.g., harmful algal blooms and disease), have contributed to a significant decline in coral reef ecosystem health (Wilkinson 2000, 2002). In response to the documented worldwide decline of coral reef ecosystems and in order to preserve and protect the biodiversity, health, heritage, and social and economic

*An **ecosystem** is a geographically specified system of organisms, the environment, and the processes that control its dynamics. Humans are an integral part of an ecosystem.*

value of U.S. coral reef ecosystems, the U.S. took two key actions:

- (1) On June 11, 1998, President William Jefferson Clinton issued Executive Order 13089: Coral Reef Protection (E.O. 13089), which set forth policies to enhance the role of Federal agencies in coral reef conservation and established the U.S. Coral Reef Task Force (USCRTF), an interagency group consisting of twelve Federal agencies and governors from seven states, territories, and commonwealths.
- (2) On December 23, 2000, the U.S. Congress enacted the Coral Reef Conservation Act of 2000 (CRCA; 16 U.S.C. 6401 et seq.). The CRCA authorized the Secretary of Commerce to establish a national program and conduct mapping, monitoring, assessment, restoration, scientific research, and other activities benefiting the understanding, sustainable use, and long-term conservation of coral reef ecosystems.

As authorized by the CRCA, the Secretary of Commerce established the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Conservation Program to carry out the mandates laid out in the CRCA and the guidelines set forth in E.O. 13089, including supporting effective ecosystem-based management and sound science to preserve, sustain, and restore the condition of coral reef ecosystems. The NOAA Coral Reef Conservation



Figure 2. Raccoon butterflyfish, *Chaetodon lunula*, among coral, *Porites* spp. (Hawaii). Photo credit: Andy Bruckner, NOAA Fisheries.

Program is implemented by four NOAA line offices – the National Ocean Service, the National Marine Fisheries Service, the National Environmental, Satellite, and Data Information Service, and the Office of Oceanic and Atmospheric Research.

Working with USCRTF partner agencies, non-governmental organizations, and other stakeholders, the NOAA Coral Reef Conservation Program developed both a national plan and a national strategy to conserve coral reefs in response to E.O. 13089 and the CRCA. In March 2000, the USCRTF's *National Action Plan to Conserve Coral Reefs* (National Action Plan) was adopted as the first national blueprint for U.S. action to address the loss and degradation of coral reef ecosystems (USCRTF 2000). In June 2002, NOAA, in collaboration with USCRTF members, published *A National Coral Reef Action Strategy* (National Action Strategy) as required by the CRCA to provide information on major threats and needs, identify priority actions needed to achieve the goals outlined in the National Action Plan and the CRCA, and track progress in achieving these goals and objectives (NOAA 2002a). Regarding research, the National Action Strategy identified two necessary actions: (1) conduct strategic research to provide critical information on the underlying causes of reef decline; and (2) increase the understanding of the social and economic factors of conserving coral reefs.

CORAL REEF RESEARCH PLANNING IN NOAA

NOAA is a science-based agency serving a large and diverse community of users and stakeholders in the United States and abroad. Earth system variability is dynamic and occurs at local, regional, and global levels, as well as multiple time scales from minutes to decades and longer. The goal of NOAA's research is to identify and improve the measurement of these many variables; to advance understanding of the physical, chemical, and biological processes in the atmosphere, oceans, and land-surface; and to enable predictions of future events and changes. The expertise needed to do this research encompasses many disciplines; therefore, the research approach must be interdisciplinary and must integrate the study of the natural environment with human activities and societal needs.

NOAA supports internal research to respond to immediate research needs, including those required by legislative and judicial mandates, to sustain long-term monitoring and modeling capabilities, and to ensure that research is forward-looking and responsive to programmatic



Figure 3. The orange cup coral, *Tubastrea coccinea*, a native to the Indo-Pacific, has been recorded in Florida waters growing on steel structures. To date, the alien coral has not been documented as invasive, however, very little is known regarding its distribution and abundance in the western Atlantic. Photo credit: Andy Bruckner, NOAA Fisheries.

needs. While the agency maintains and relies on internal expertise in coastal and ocean sciences, NOAA also relies on external research partners to complement and augment NOAA's internal research capabilities, to provide critical expertise in areas not fully represented inside the agency, and to share new ideas and technologies. NOAA's research partnerships engage other Federal agencies; academia; the private sector; state, territorial, commonwealth, local, and tribal governments; and the international community; and are critical to ensuring that decision-making by resource managers, Congress, and others is based on the best available science.

NOAA has identified research as a major cross-cutting priority in the *NOAA Strategic Plan*, demonstrating its firm commitment to support high-quality research as the underpinning of its environmental assessment, prediction, and ecosystem management missions (NOAA 2005c). Research is the cornerstone on which to build and improve ecosystem-based management and resource management decisions. Research planning and prioritization are key steps to address the information needs of NOAA's users as indicated in both the five-year *NOAA Research Plan* (NOAA 2005a) and the 20-year *NOAA Research Vision* (NOAA 2005b).

This document – the *NOAA Coral Reef Ecosystem Research Plan* – builds on the strategies identified in *NOAA's Strategic Plan*, the five-year *NOAA Research Plan*, the 20-year *NOAA Research Vision*, the National Action Plan, the National Action Strategy, the *Final Report of the U.S. Commission on Ocean Policy* (USCOP 2004), and the Bush Administration's response to the U.S. Commission on Ocean Policy: the *U.S. Ocean Action Plan* (Bush 2004); and identifies key directions for NOAA's research on coral reef ecosystems for fiscal years (FY) 2007 through FY 2011. As this Plan only covers five years, it is intentionally focused on research with short-term outcomes of providing coastal and ocean managers with scientific information and tools to help preserve, sustain, and restore coral reef ecosystems. This five-year Plan will also be used as a tool to identify longer-term coral reef research directions.

It is important to note that the majority of coral reefs in the U.S. and Pacific Freely Associated States (i.e., Republic of Palau, Republic of the Marshall Islands, and the Federated States of Micronesia) are not managed solely by NOAA. The primary managers for U.S. coral reefs include state, territorial, and commonwealth government agencies

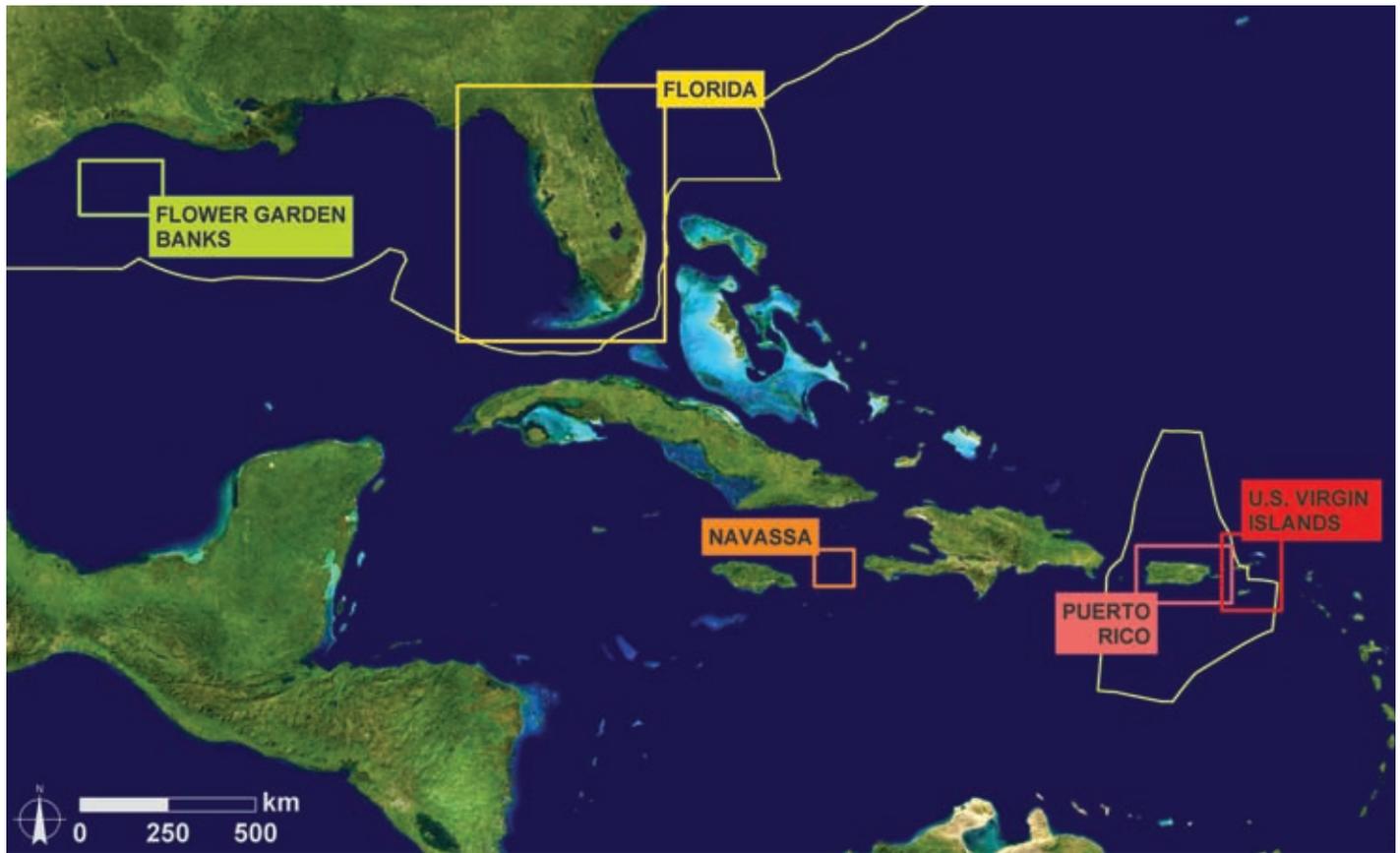


Figure 4. A map depicting the location of U.S. coral reef ecosystems in the Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea. Map: A. Shapiro. Source: Waddell (2005).

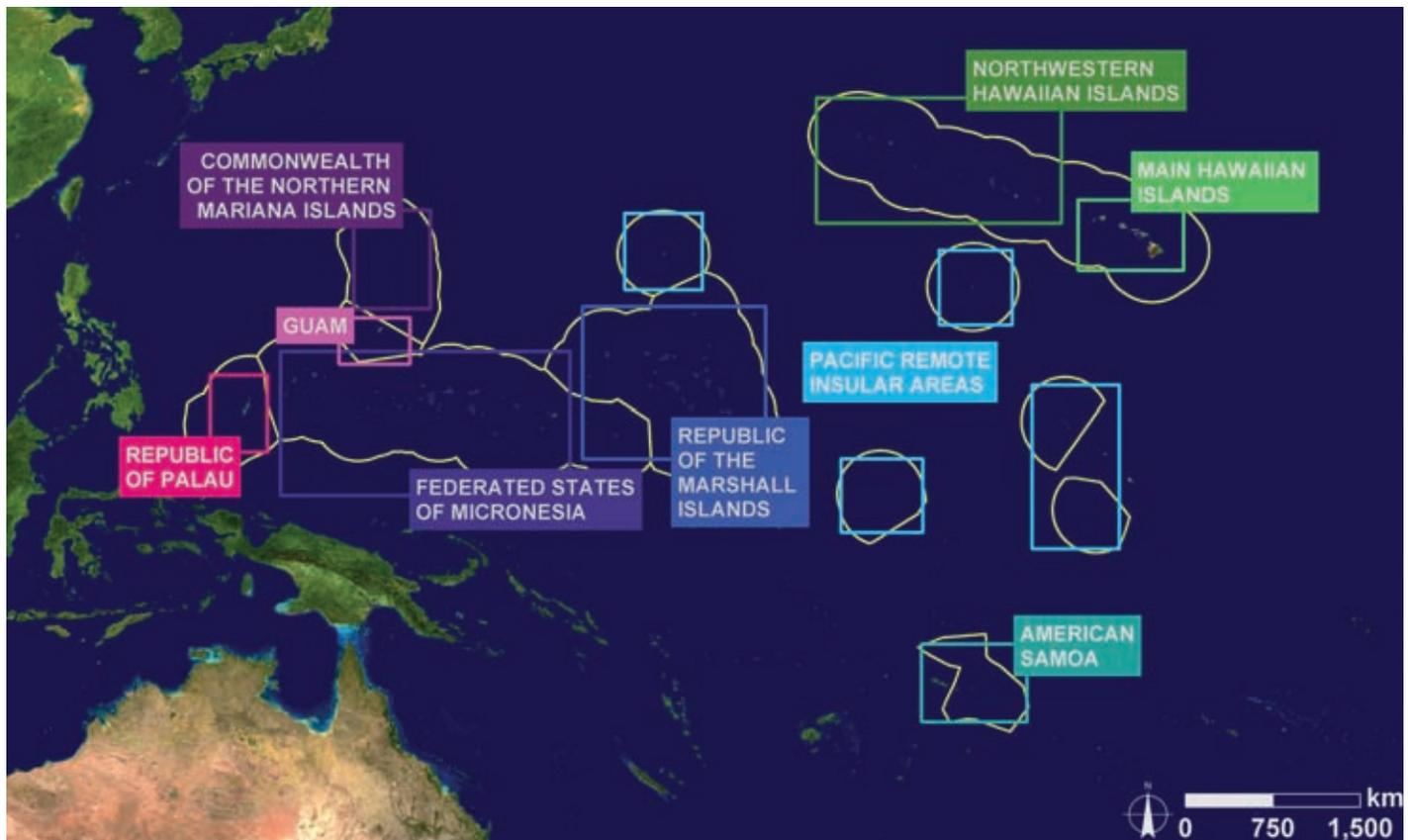


Figure 5. A map depicting the location of U.S. coral reef ecosystems in the Pacific Ocean. Map: A. Shapiro. Source: Waddell (2005).

in Florida, Puerto Rico, the U.S. Virgin Islands, Hawaii, Guam, American Samoa, and the Commonwealth of the Northern Mariana Islands; and several Federal agencies, including the U.S. Fish and Wildlife Service (FWS), the National Park Service, the U.S. Department of Defense, and NOAA. It is not the intent of this Plan to pre-empt any existing management authorities. As the responsibility for managing coral reefs falls on numerous agencies, it is of utmost importance that NOAA works with the primary managers to identify research priorities and coordinate, communicate, and conduct collaborative research projects for which results can be directly incorporated into existing management plans or used as a basis to make major revisions to management plans. Without this type of coordination, coral reef ecosystem research may not target the information needs of resource managers or support the furthering of an ecosystem approach to management.

PURPOSE

The purpose of the NOAA Coral Reef Ecosystem Research Plan is to identify priority research needs and guide NOAA-funded coral reef ecosystem research for FY 2007 through FY 2011, including research conducted through extramural partners, grants, and contracts. The Plan is also designed to be a resource to other non-NOAA entities that fund and/or conduct research in coral reef ecosystems. This Plan is intended to be a flexible, evolving document that allows new requirements for research to be addressed as appropriate. Annual implementation plans will allow refinement of the research needs identified in this Plan to further focus limited research funds, respond to emerging issues and changing priorities, and take advantage of technologies developed during the next five years.

SCOPE

The NOAA Coral Reef Ecosystem Research Plan covers all shallow coral reef ecosystems under the jurisdiction of the United States and the Pacific Freely Associated States (Table 1; and Figures 4 and 5); and is written for a broad audience, including resource managers, scientists, policymakers, and the public.

This Research Plan addresses the USCRTF focus areas – land-based pollution, overfishing, recreational overuse and misuse, climate change and coral bleaching, and coral disease – identified at the eighth meeting of the USCRTF on October 2 to 3, 2002 in San Juan, Puerto Rico (USCRTF 2002), as well as other priority threats to coral reef ecosystems – destructive fishing practices, invasive species, other coastal uses, and extreme events. The Plan’s research needs were developed based on recommendations from workshop reports, technical reports, peer-reviewed articles, and direct input and review by the representative government agencies and governments of the USCRTF, coral reef managers, scientists, and other key stakeholders. (See *References* and *Appendix A: Additional Supporting Documents* for a list of documents that were used to prepare this Research Plan. For information on the process used to develop the Research Plan see *Appendix B: Developing the Research Plan*.)

This plan identifies research needs to improve the management of tropical and sub-tropical coral reef ecosystems including mangroves, seagrasses, and hard bottom communities, and warm water, light-dependent, hermatypic deep water shelf and slope corals that are typically found between 50 to 100 meters (m). Coral reef ecosystems, as defined in 16 U.S.C. 6409, are corals

Table 1. Regions covered by the NOAA Coral Reef Ecosystem Research Plan.

Atlantic	Pacific
Florida Florida Keys Southeast Florida Eastern Gulf of Mexico (West Florida Shelf) Flower Garden Banks Puerto Rico U.S. Virgin Islands Navassa Island	The Hawaiian Islands Main Hawaiian Islands Northwestern Hawaiian Islands Commonwealth of the Northern Mariana Islands Guam American Samoa U.S. Pacific Remote Insular Areas Pacific Freely Associated States Republic of the Marshall Islands Republic of Palau Federated States of Micronesia



Figure 6. Diver amongst a stand of staghorn corals, *Acropora cervicornis*. Photo credit: NOAA's Undersea Research Program.

and other species of reef organisms (including reef plants) associated with coral reefs and the non-living environmental factors that directly affect coral reefs, that together function as an ecological unit in nature (Figure 6). The following topics are not included in this Research Plan:

- **Deep-Sea Coral Ecosystems:** This Research Plan does not identify research needs for deep-sea coral ecosystems; however, it does recognize the importance of deep-sea coral ecosystems and the need for further research to better understand these ecosystems. Deep-sea coral ecosystems (also referred to as cold-water coral ecosystems) occur deeper than 50 m and often consist of both reef-like structures and/or thickets, other species of organisms associated with these deep-sea coral habitats, and the non-living environmental factors that directly affect deep-sea corals, that together function as an ecological unit in nature (Puglise et al. 2005). Deep-sea corals are not light dependent and do not contain symbiotic algae. *Note: Deep-sea coral ecosystem research priorities will be identified in a separate document.*
- **International Research Priorities:** This Research Plan does not identify research needs for NOAA-supported research on international coral reef ecosystems.

However, it does recognize the importance of developing an active dialogue and coordinating research activities with other international efforts so that research findings can be effectively compared with other programs and locations.

- **State of the Coral Reef Ecosystems:** This Research Plan does not review the current state of knowledge on reef condition for each region, except as it applies to specific management objectives and research needs. For information on the status and trends of coral reef ecosystems, refer to the report entitled *The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2005* (Waddell 2005).

CORAL REEF RESEARCH PLAN FRAMEWORK

The NOAA Coral Reef Ecosystem Research Plan is presented in two sections: (1) Part I: National Priorities; and (2) Part II: Regional Priorities (Table 2).

Part I is national in scope and identifies: (1) the role of research in management, including a review of the major stressors and threats facing coral reef ecosystems and an overview of stressor-associated research priorities;

(2) the role of mapping and monitoring in management-driven research programs; (3) a discussion of the tools and technologies necessary to conduct research and to manage ecosystems (e.g., marine protected areas [MPAs] and habitat restoration); (4) a discussion of the importance of transferring science and technology into operations; and (5) the importance of using targeted outreach and education to translate research results to improve management decisions.

Part II is regional in scope and reviews the major stressors for coral reef ecosystems in each region under the jurisdiction of the U.S. and the Pacific Freely Associated States, and identifies key management objectives specific to each region and the research needed to help address the stated management objectives. The discussions of individual jurisdictions in Part II include a list of specific management objectives followed by linked research needs. Several of the identified research needs are national in scope and have been identified in a *Jurisdiction-Wide* section in Part II, whereas the individual regional sections identify research needs that are *Jurisdiction-Specific*. A stand-alone research plan for each region would include both the national and regional research needs.

EVALUATING SUCCESS

Measuring performance and effectively communicating results is critical. Research activities supporting the NOAA Coral Reef Ecosystem Research Plan must include performance measures that are linked to defined management objectives, along with mechanisms to ensure accountability and high quality, including rigorous and independent peer-review procedures.

NOAA is a mission-driven agency with stewardship responsibilities for marine living resources. The activities conducted by NOAA, as well as other Federal agencies, are driven by requirements (e.g., legal mandates, E.O.s, and treaties) and performance measures (i.e., activities are evaluated as required by the Government Performance and Results Act of 1993 [GPRA] and the Office of Management and Budget’s Program Assessment Rating Tool). The primary and secondary requirement drivers for the NOAA Coral Reef Ecosystem Research Plan are listed below and detailed in Appendix C:

Table 2. Framework of the NOAA Coral Reef Ecosystem Research Plan.

PART I: NATIONAL RESEARCH PRIORITIES	PART II: REGIONAL RESEARCH PRIORITIES
<ul style="list-style-type: none"> ◇ Research Supporting Management <ul style="list-style-type: none"> ⊙ Fishing ⊙ Pollution ⊙ Coastal Uses ⊙ Invasive Species ⊙ Climate Change ⊙ Extreme Events ◇ Technology Supporting Research and Management <ul style="list-style-type: none"> ⊙ Marine Protected Areas ⊙ Habitat Restoration ◇ Transferring Science and Technology into Operations ◇ Outreach and Education: Translating Research, Improving Management 	<ul style="list-style-type: none"> ◇ Jurisdiction-Wide Research Needs ◇ Jurisdiction-Specific Research Needs – Atlantic Ocean <ul style="list-style-type: none"> ⊙ Florida <ul style="list-style-type: none"> ◆ Florida Keys ◆ Southeast Florida ◆ Eastern Gulf of Mexico (West Florida Shelf) ⊙ Flower Garden Banks ⊙ Puerto Rico ⊙ U.S. Virgin Islands ⊙ Navassa Island ◇ Jurisdiction-Specific Research Needs – Pacific Ocean <ul style="list-style-type: none"> ⊙ The Hawaiian Islands <ul style="list-style-type: none"> ◆ Main Hawaiian Islands ◆ Northwestern Hawaiian Islands ⊙ Commonwealth of the Northern Marina Islands ⊙ Guam ⊙ American Samoa ⊙ U.S. Pacific Remote Insular Areas ⊙ Pacific Freely Associated States <ul style="list-style-type: none"> ◆ Republic of the Marshall Islands ◆ Republic of Palau ◆ Federated States of Micronesia

Primary Requirements:

- ◆ CRCA (16 U.S.C. 6401 et seq.)
 - ◇ National Coral Reef Action Strategy (2002)
 - ◇ The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States (2002, 2005)
- ◆ E.O. 13089: Coral Reef Protection (1998)
 - ◇ National Action Plan to Conserve Coral Reefs (2000)
 - ◇ USCRTF Local Action Strategies (2005-2007)
- ◆ Magnuson-Stevens Fisheries Conservation and Management Act, as amended by the Sustainable Fisheries Act (16 U.S.C. 1801 et seq.)
- ◆ National Marine Sanctuaries Act (16 U.S.C. 1431 et seq.)
- ◆ E.O. 13178: Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve (2000)
- ◆ E.O. 13196: Final Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve (2001)
- ◆ Presidential Proclamation: Establishment of the Northwestern Hawaiian Islands Marine National Monument (2006)

Secondary Requirements:

- ◆ Coastal Zone Management Act (16 U.S.C. 1451 et seq.)
- ◆ Endangered Species Act (16 U.S.C. 460 et seq.)
- ◆ E.O. 13112: Invasive Species (1999)
- ◆ E.O. 13158: Marine Protected Areas (2000)
- ◆ GPRA (31 U.S.C. 1115 et seq.)
- ◆ Marine Mammal Protection Act (16 U.S.C. 1361 et seq.)
- ◆ Marine Turtle Conservation Act of 2004 (16 U.S.C. 6601 et seq.)

Links to the NOAA Strategic Plan

The NOAA Coral Reef Ecosystem Research Plan links to the following *NOAA Strategic Plan* outcomes and objectives for the Ecosystem Mission Goal, for which the NOAA Coral Reef Conservation Program activities are directed towards achieving:

Ecosystem Goal Outcomes

- Healthy and productive coastal and marine ecosystems that benefit society.
- A well-informed public that acts as steward of coastal and marine ecosystems.

Ecosystem Goal Objectives

- Increase number of fish stocks managed at sustainable levels.

- Increase number of protected species that reach stable or increasing population levels.
- Increase number of regional coastal and marine ecosystems delineated with approved indicators of ecological health and socioeconomic benefits that are monitored and understood.
- Increase number of invasive species populations eradicated, contained, or mitigated.
- Increase number of habitat acres conserved and restored.
- Increase portion of the population that is knowledgeable of and acting as stewards for coastal and marine ecosystem issues.
- Increase number of coastal communities incorporating ecosystem and sustainable development principles into planning and management.

The NOAA Coral Reef Conservation Program outcomes that contribute to achieving NOAA's Ecosystem Goal outcome and objectives are:

NOAA Coral Reef Conservation Program Outcomes

- The impacts of climate change and coral disease are understood and approaches to enhance coral reef resiliency are developed and implemented.
- Direct physical impacts from maritime industry and natural/non-natural hazards are reduced.
- Impacts from coastal uses and land-based activities are reduced.
- Overfishing in coral reef ecosystems is reduced and other adverse impacts from commercial and recreational fishing are minimized.

Research is not intended to meet the NOAA Strategic Plan and the NOAA Coral Reef Conservation Program outcomes and objectives alone. Rather, research serves as a mechanism to help meet the aforementioned outcomes and objectives. Successful research supported by NOAA will provide information that improves the understanding of coral reef ecosystem function and condition, including the factors (i.e., stressors and natural variability) that determine that condition, and supports development and evaluation of tools and approaches to assess the ecological and economic impacts of stressors, reduce stressors, and restore reefs.

Part I: National Research Priorities



School of Hawaiian squirrelfish (French Frigate Shoals, Northwestern Hawaiian Islands). Photo credit: James Watt.

Coral resource managers should have the most up-to-date scientific information to facilitate management of the resources under their purview. The intent of this Research Plan is to guide the full suite of NOAA's coral reef ecosystem research capabilities, both internal and external, toward meeting this challenge within the context of limited resources.

Importance of Mapping and Monitoring

Sound management of coral reef ecosystems requires scientifically-based information on their status (or condition), the causes and consequences of that condition, forecasts of their future condition, and the costs and benefits of possible management actions to maintain or improve their condition. Even more fundamental is the identification and characterization of each coral reef ecosystem, including the physical location (boundaries), spatial extent, physical and biological characteristics, and characterization of the social and human aspects of coral reef ecosystems. Baseline information on the economic, cultural, institutional, and social values, as well as human use patterns, of coral reef ecosystems should be determined. Because coral reef ecosystems are dynamic, even in their physical attributes, continuous research is required to quantify changes and understand the processes and rates at which they occur. Thus, the map products (mapping) and long-term data collections (monitoring) necessary for sound management decisions are as much a part of the research agenda as the quantitative analyses applied to these products.

Mapping and monitoring provide information fundamental to understanding the history, current state, and future condition of coral reef ecosystems and are cornerstones to ecosystem-based management. Long-term monitoring also provides data to allow a rigorous evaluation of whether or not management programs are working. Historically, monitoring programs have focused on determining the condition of ecologically or economically important species and/or specific habitat types (e.g., emergent reefs) by documenting a combination of static (e.g., cover and abundance at a point in time) and process-oriented (e.g., recruitment, growth, and condition) parameters. Surveys have also recorded the presence and abundance of major corallivores or coral predators (e.g., crown-of-thorns starfish [COTS]) and herbivores (e.g., sea urchins). The development of an ecosystem approach to management will require that programs expand their scope to address the broadest set of management issues across multiple

habitat types, including defining the 'natural' ecosystem or what is considered normal, documenting change and environmental conditions (e.g., in situ sea surface temperature, photosynthetically active radiation [PAR], and ocean color), evaluating the effects of environmental stressors, identifying the causes of decline, and analyzing human populations and their use (or non-use) of coral reef ecosystems. An ecosystem approach to management requires knowledge of the natural ecosystem, including the guilds or trophic levels that are normally present and interactions between these; how communities may vary with latitude, season, and geomorphology; what environmental variables define community composition; as well as an understanding of processes and outcomes necessary for sustainability, including the role of surrounding ecosystems.

Mapping and monitoring efforts are most useful when data are integrated at the appropriate spatial and temporal scales and aligned closely with process-oriented research designed to help understand the causes of spatial and temporal variability and change. Additionally, better coordination of mapping, monitoring, and research projects among NOAA, other Federal, state, territorial, commonwealth, and local agencies, coral resource managers, and local reef specialists would allow for the maximum amount of information to be obtained from a single sample or endeavor and increase coverage by reducing overlap among monitoring programs.

Coral reef ecosystems and individual reefs can vary over space (spatially) and time (temporally). Therefore, monitoring programs need to consider: (1) the spatial resolution necessary to document the spatial mosaic defining coral reef ecosystems (e.g., across multiple habitat types moving from nearshore to offshore, among and within reefs, and across depths); (2) the sampling frequency needed to try to understand the causes of ecosystem change; and (3) the variety of data required to make management decisions. Sampling frequency for monitoring programs usually ranges from rapid assessments conducted over relatively short time scales of days and weeks that characterize broad patterns of community structure or episodic and unpredictable events (e.g., physical damage caused by ship groundings or storms, or biological events such as coral disease and coral bleaching) to monitoring that occurs repetitively at the same location(s) over many years.



Figure 7. Tiger grouper, *Mycteroperca tigris*, on a star coral colony, *Montastraea franksi* (Flower Garden Banks National Marine Sanctuary). Groupers are harvested Caribbean-wide and in the U.S. The tiger grouper is included under the Grouper Snapper Fishery Management Plan for Federal waters, although there is no specific fishery targeting this species. Photo credit: Andy Bruckner, NOAA Fisheries.

Decisions about what and when to monitor should be based on the management and scientific questions being asked. Both short-term (less than five years) and long-term (greater than five years) assessments are needed to understand ecosystem variation. For example, short-term monitoring programs intended to provide early warning of coral reef ecosystem changes and document the status of economically and ecologically important reef species (Figure 7). Short-term assessments can document acute changes impacting coral condition, such as El Niño Southern Oscillation events and coastal development (e.g., dredging and beach renourishment projects). Long-term assessments document changes caused by factors that operate at decadal scales, such as the influence of declining fish stocks, as well as the potential impacts of increasing atmospheric carbon dioxide and the potential associated temperature increases.

When linked to targeted research programs, mapping and monitoring programs can improve identification and understanding of threats to coral reef ecosystems by providing baseline characterizations of coral condition and habitat, as well as contributing to solving high priority management issues. Additionally, characterizing and monitoring economic, demographic, and institutional changes may also help resource managers anticipate impacts from anthropogenic influences on coral reef ecosystems. Mapping and monitoring efforts record change and the condition of the resource, and characterize the societal aspects of the resource; while research examines the causes and predicts the impacts of changes on the condition of the resource. The ability to ascribe declines in ecosystem condition to a stressor is often confounded by the fact that stressors often act synergistically. In situations like these, it is important

for research to be conducted in tandem with monitoring programs to try to understand the causes of ecosystem decline.

NOAA is committed to working with its partners to support a long-term environmental monitoring program and the mapping of all U.S. shallow-water coral reefs and associated ecosystems. This commitment addresses the USCRTE goal to develop and implement a nationally coordinated, long-term program to inventory, assess, and monitor U.S. coral reef ecosystems. NOAA monitoring and mapping efforts should be coordinated with partners from Federal, state, territory, commonwealth, and local government agencies; non-governmental organizations; and academia to minimize duplication and maximize data collection. NOAA coral monitoring efforts represent a small part of the growing national coastal monitoring network.

RESEARCH SUPPORTING MANAGEMENT

The condition of ecosystems is impacted by the singular or combined effects of five stressors: land and resource use (herein referred to as fishing and coastal uses), climate change, pollution, extreme events, and invasive species (OSTP 2001). Interactions between these stressors, as well as natural variability over space and time can also be involved in determining ecosystem condition. These generalizations are applicable to coral reef ecosystems, and it is the goal of NOAA's coral reef ecosystem research to provide sound science to enable effective ecosystem-based management by identifying the stressors affecting ecosystem condition, determining the processes by which they affect ecosystems, identifying their short- and long-term impacts, identifying strategies to mitigate these impacts, and forecasting future ecosystem conditions with and without management intervention. It is the intent of the NOAA Coral Reef Ecosystem Research Plan to identify priority research needs for NOAA-supported coral reef ecosystem research for FY 2007 through FY 2011. Research priorities are based on management-driven information needs as identified by resource managers, scientists, and other key stakeholders.

Conservation and management of coral reefs require a multidisciplinary approach that acknowledges the complexity and multiple dimensions of coral reef ecosystems (e.g., anthropogenic, ecological, and biological) and their dynamic nature, and the need for cooperatively implementing management measures, as management

responsibility for coral reef ecosystems often crosses local, commonwealth, territory, state, Federal, and international jurisdictions. Therefore, maintaining healthy coral reef ecosystems requires a balance between not only ecological functions, but the many different types of human uses of those ecosystems.

Conservation and management of coral reefs also requires recognition that coral reef ecosystems are one piece of much larger marine ecosystems. Within NOAA, ecosystem research and management activities are organized into eight regional ecosystems adjacent to the U.S. coasts (i.e., Northeast Shelf, Southeast Shelf, Caribbean, Gulf of Mexico, Great Lakes, California Current, Alaska, and Pacific Islands). These eight regional ecosystems in turn link into other larger marine ecosystems. For example, the Gulf Stream current links the coral reef ecosystems of the Southeast U.S. to those of the Caribbean and Gulf of Mexico.

Coral reef ecosystem protection and conservation require a strong legal framework that provides managers with a variety of tools, including zoning ordinances, permit programs, water quality criteria and standards, management plans, regulations, and enforcement capabilities that operate across multiple jurisdictions. A strong legal framework will require Federal, state, territory, commonwealth, and local government agencies to coordinate and commit to conducting mapping, monitoring, and research, as well as implementing management measures, cooperatively. This framework should also take into consideration traditional and customary management practices of the U.S. Pacific Islands in revitalization and identification of resource use practices to garner the support of the indigenous communities. Policymakers and the public are also an integral part of the management process.

Understanding societal views and processes and their affects on coral reef ecosystem condition is integral to improving management of coral reef resources. Examples of dynamic societal processes that may have far-reaching impacts on coral reef ecosystems include rapid population growth, global movements of humans, the mixing of cultures and loss of traditional cultural integrity, globalization of economies, and advances in technology. The role of social science in coral reef ecosystem management is to improve the understanding of these changing societal processes by determining how society

is currently choosing to use coral reef ecosystems and estimating the social and economic costs and benefits of those uses from an ecosystem perspective, including the biological costs and benefits to the resource associated with these uses. Social science research could also help characterize attitudes, perceptions, and beliefs within different segments of the population and examine how these factors influence human behaviors related to both the use and conservation of coral reef ecosystems.

Traditionally, coral reef ecosystem research has focused on the impacts that human activities have on the ecosystem as measured by one or more environmental metrics. While we are beginning to understand the ecology of these systems more fully, Federal, state, territory, and commonwealth management agencies still lack information on the social, cultural, and economic aspects of coral reef ecosystems. For example, economic valuation of annual and net benefits of goods and services provided by U.S. coral reef ecosystems are key needs for managers to show the importance of the resource in economic terms. Yet economic valuations have only been completed for the four-county area of southeast Florida – Palm Beach, Broward, Miami-Dade and Monroe counties (Johns et al. 2001), the Main Hawaiian Islands (Cesar et al. 2002), American Samoa (JacobsGIBB Ltd 2004), Guam (van Beukering et al. 2006a), and Commonwealth of the

Northern Mariana Islands (van Beukering et al. 2006b). This critical information gap jeopardizes the nation's ability to make science-based decisions that include the human environment, as well as the natural environment.

Research of both natural and physical sciences needs to be integrated with socioeconomic research to develop management actions that are compatible with the resources and their users. Many factors contribute to change in coral reef ecosystems (Table 3), but it is difficult to ascribe widespread decline to single factors locally or regionally because stressors can vary in occurrence and severity across regions and sometimes from reef to reef and have possible cumulative and synergistic impacts. The complexity of interactions among stressors that affect coral reefs makes it difficult to sort out the primary stressors responsible. The coral reef ecosystem decline now being witnessed is due to the integrated consequences of many stressors.

The next sections summarize the major threats to coral reef ecosystems as identified by the USCRTF, and identifies key national-level research priorities. The major threats discussed are: fishing, pollution, coastal uses, invasive species, climate change, and extreme events. These categories parallel research categories found in Part II of this Plan.

Key Socioeconomic Research Questions for Coral Reef Ecosystems:

- *Who are the users of coral reef ecosystems?*
- *What are the social and economic uses of coral reef ecosystems?*
- *What are the social and economic costs and benefits of those uses?*
- *What are the impacts of social and economic uses to these ecosystems?*
- *What are the relationships between uses and a series of environmental metrics?*
- *What are the interactions between human use activities in coral reef ecosystems?*
- *How do societal reactions to changes in coral reef ecosystems impact human behavior and how do these behavioral changes affect the coral ecosystem?*
- *How do different laws and policies influence human use and protection of coral reef ecosystems?*
- *In what ways do local knowledge and scientific information influence how adjacent communities use and protect coral reef resources?*
- *What impacts do changing human demographics have on coral reef ecosystems?*
- *What (non-monetary) values does society hold or assign to coral reef ecosystems?*
- *How well do people understand coral reef ecosystems (biological and physical elements, scarcity, and sensitivity)?*

Part I: National Research Priorities

		Climate change & coral bleaching	Diseases	Tropical storms	Coastal development and runoff	Coastal pollution	Tourism and recreation	Fishing	Trade in coral and live reef species	Ships, boats, and groundings	Marine debris	Aquatic invasive species	Security training activities	Offshore oil and gas exploration	Other	Jurisdictional Composite Trend	Δ (2002 to 2004)
USVI	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	14	↑
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	16	
Puerto Rico	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	18	↓
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	11	
Navassa	2002															N/A	
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	4	
Florida	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	17	↑
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	18	
Flower Gardens Banks	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	3	↑
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	4	
MHI	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	17	-
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	17	
NWHI	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	9	↓
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	5	
American Samoa	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	11	↓
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	*	9	
PRIAs	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	7	↓
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	5	
Marshall Islands	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	8	↓
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	7	
Federated States of Micronesia	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	11	↓
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	6	
CNMI **	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	14	↓
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	9	
Guam	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	8	↑
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	13	
Palau	2002	■	■	■	■	■	■	■	■	■	■	■	■	■	■	11	↓
	2004	■	■	■	■	■	■	■	■	■	■	■	■	■	■	6	
Stressor Change Assessment	2002	12	6	7	19	17	9	18	9	17	10	10	5	1	8		
	2004	16	7	8	18	11	9	20	5	13	7	5	2	1	4		
Δ (2002 to 2004)		↑	↑	↑	↓	↓	-	↑	↓	↓	↓	↓	↓	-	↓		
Temporal Composite Threat		■	■	■	■	■	■	■	■	■	■	■	■	■	■		

Fishing

A fishery is comprised of the species sought (including the incidental or unintended catch), the habitat in which they live, and the humans conducting the fishing activities. Coral reef ecosystems support important commercial, recreational, and subsistence food fisheries in the U.S. and around the world. Fishing also plays a social and cultural role in many island communities (Figure 8). The biodiversity of reefs supports the aquarium and aquaculture industries, biomedical industry, and other commercial industries. The management of coral reef fisheries falls across several groups, including NOAA through the regional fishery management councils, and state, territory, commonwealth, and local agencies.

Successful management of coral reef fisheries through the balancing of society's desire to attain the economic benefits from these resources with the biological requirements for sustaining them depends critically upon the best available scientific information. Implementation of an ecosystem-based approach to fisheries management will require the development of practical approaches that support shifting from single species management to an ecosystem approach.

Research is needed to address three key fishing-related threats to coral reef ecosystems — fishing and overfishing, destructive fishing, and the effects of marine aquaculture — and the social and economic costs and benefits of these threats. The social importance of activities such as

fishing can mobilize groups to support or oppose different management measures. Thus, it is important to understand inter-group relationships, perceptions, beliefs, and their links to particular behaviors. Additionally, research is needed to better understand the impacts of fishing-related activities on species of concern, including threatened, endangered, rare, and protected migratory species that are dependent on coral reefs (e.g., low reef islets and lagoons) for their survival, such as monk seals, sea turtles, pearl oysters, giant clams, conchs, coconut crabs, humphead wrasse, bumphead parrotfish, groupers, and rare ground-nesting seabirds.

Fishing and Overfishing: Overfishing of high value predators and important herbivores has been documented on nearly all U.S. inshore reefs near populated areas (Figure 9; Turgeon et al. 2002), and is spreading to deeper reefs and more remote locations. In general, we know the causes of this decline — direct overexploitation of fish and invertebrates by recreational, subsistence, and commercial fisheries. However, the full ramifications of overfishing are poorly understood and present a major challenge to resource managers and scientists. There is increasing evidence that overfishing, including historical overfishing of apex predators, herbivores, and keystone species on reefs not only results in shifts in fish size, abundance, species composition, and genotypic diversity, but also is a major driver contributing to the degradation of coral reef ecosystems. Increasing the state of knowledge on the potential cascading effects of reduced predator and herbivore abundances

Table 3. A comparison of the 2002 and 2004 perceived levels of threat to coral reef ecosystems in the U.S. and [Pacific Freely Associated States], based on expert opinion. Red squares represent high threat (2 points), orange represents moderate threat (1 point), and yellow represents little or no threat (0 points). Scores were tallied horizontally to calculate the level of threat from individual stressors across jurisdictions and vertically to calculate overall threat by jurisdiction for all stressors combined. Red arrows indicate a net increase in threat level, and green arrows indicate a net decrease in threat level. Horizontal bars indicate no change. Only data for 2004 are available for Navassa.

**Following the 2000 census, population growth emerged as a major issue in American Samoa; the high threat rating was assigned to the Coastal Development and Runoff threat to be consistent within the table.*

***For the Commonwealth of the Northern Mariana Islands, 2002 data were based on the southern islands only, while 2004 data include the northern islands; the perceived threat for the southern islands did not change from 2002 to 2004. Note: The actual impacts of each threat category will likely vary widely within and among regions.*

This table has been reprinted with permission from Waddell (2005).

and sizes, by using fished and non-fished coral reef ecosystems, are instrumental to understanding the full effect of overfishing on ecosystem functions, designing effective conservation programs, and determining the impact of management actions (e.g., fishing closures) on the sustainability of fish stocks. Understanding the drivers of overfishing (e.g., perceptions of the impacts of overfishing and resource availability), how decisions are made to exceed sustainable limits, and a thorough analysis of existing fisheries data are also key to understanding the impacts of overfishing. Research focused on the perceptions and attitudes about factors including fishery health, gear restrictions, aquaculture versus extraction of wild stocks, market conditions, regulations, and environmental conditions could help shed light on how fishers decide to target a particular species or utilize different fishing techniques.

Destructive Fishing: Indirect impacts associated with some fishing techniques and gear include: (1) physical impacts to reef environments; (2) by-catch, ghost fishing (i.e., lost or derelict fishing gear that continues to catch fish and other species), and mortality of non-target species; and (3) unauthorized fishing in closed areas. Research is needed to predict, prevent, and mitigate these indirect fishing impacts. Research should include identifying and assessing gear impacts, developing new technologies and gear to minimize these impacts, and researching and developing techniques to improve fishing surveillance, enforcement, and management of remote coral reefs.

Marine Aquaculture: Marine aquaculture is growing rapidly in regions with coral reefs, and may provide employment and decrease collection pressure on wild populations. However, if poorly sited or managed,

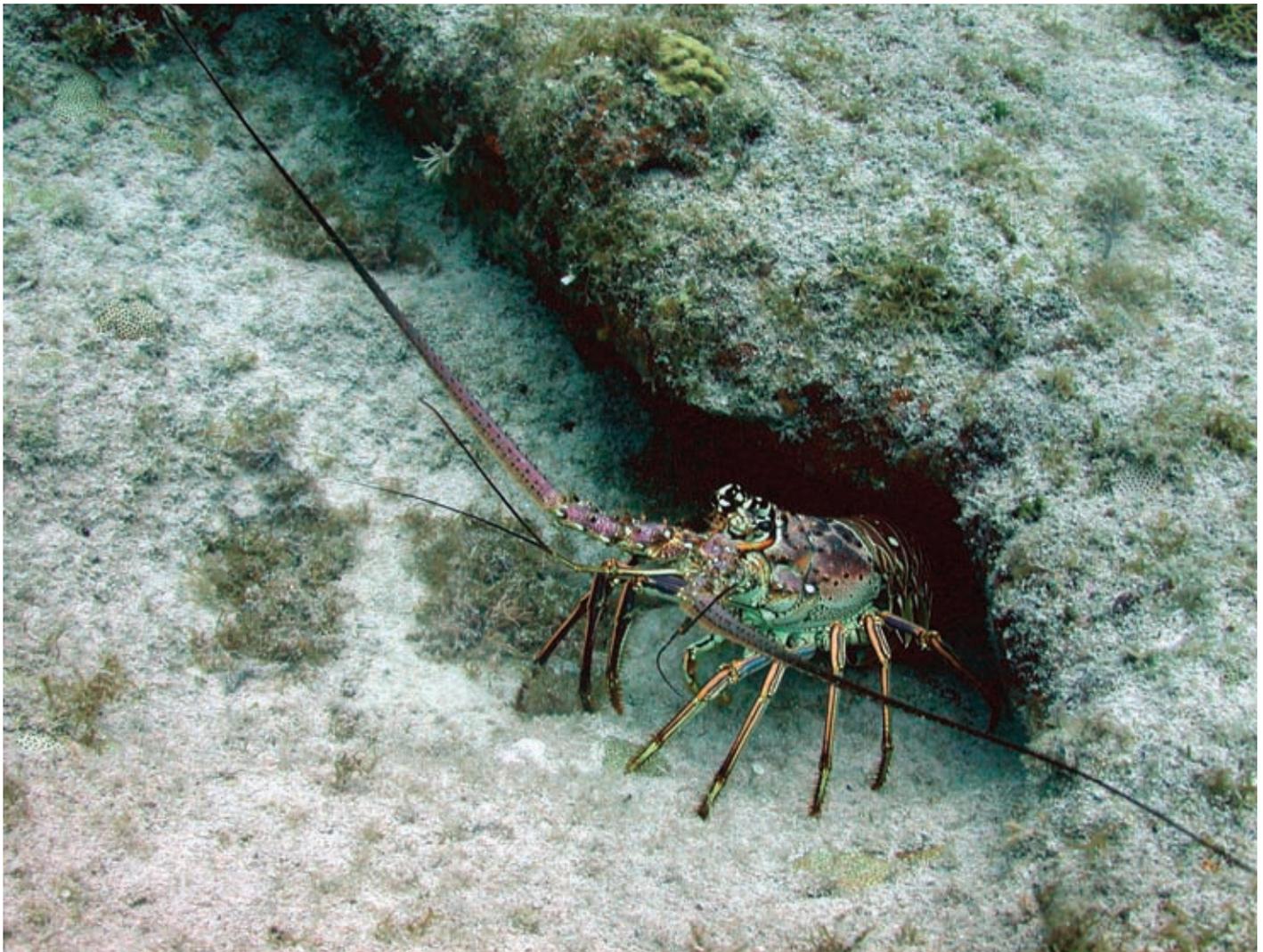


Figure 8. The spiny lobster, *Panulirus argus*, is one of the most valuable fishery species in the Caribbean. They are exported from several non-U.S. Caribbean countries. In Puerto Rico and the U.S. Virgin Islands, spiny lobsters are for local consumption only. Photo credit: Deborah Gochfeld.



Figure 9. Nassau grouper, *Epinephelus striatus*, once among the most important fishery species in the Southeastern U.S. and the Caribbean region, have been overfished in the U.S. and are currently protected from fishing in state and Federal waters. Photo credit: Craig Dahlgren.

marine aquaculture in open systems can adversely affect coral reef ecosystems by disrupting submerged land on and adjacent to reefs, serving as fish aggregation devices, introducing invasive alien species, discharging nutrients, causing disease, and reducing genetic diversity of wild stocks by allowing cultured stocks to escape and mix with wild populations. Research should provide the foundation for science-based decisions on site selections and permitted activities. Research is also needed on culturing corals for restoration activities and early life stages of marine ornamental fishes to enable reliable production of eggs to juvenile stages. Research should also help develop models to address ways to predict, contain, prevent, and mitigate the potential impacts on the genetic diversity of wild stocks and the release of opportunistic pathogens on native populations from aquaculture activities.

General research questions relevant to fishing include: How does the present-day status of fished species compare with historical abundances and sizes? How has overfishing affected trophic interactions among fish species and how have potential changes to food webs affected models used to manage fisheries, including single-species and ecosystem-based models? What is the effect of overfishing predators on ecosystem structure? What are the ecological effects of overfishing and destructive fishing practices, including the effects on non-targeted species and on benthic coral reef habitats? Why do fishers decide to employ destructive fishing techniques? What roles do habitat heterogeneity, living coral, and geographic linkages among coral reef ecosystems play as components of essential fish habitat for economically and ecologically important fisheries? How do the products of aquaculture (including species released purposefully or accidentally

and water quality pollution, where it exists) affect the structure and function of surrounding ecosystems? What are the politics associated with increasing aquaculture development and trade in farm-raised seafood (e.g., are special opportunities presented or denied to locals associated with the aquaculture industry)? What are the socioeconomic impacts of existing and proposed fisheries management plans that affect coral reef ecosystems? How do invertebrate fisheries (e.g., octopus, sea cucumbers) impact the coral reef ecosystem? How has the fishing of spawning aggregations affected fish communities? What tools can be developed to predict likely locations of spawning aggregations? How do management activities and regulations influence fishers' attitudes and perceptions? How do perceptions of scientific information, and the agencies disseminating it, shape fishers' attitudes and behaviors?

Pollution

Worldwide, the threat to coral reef ecosystems from pollution is surpassed in severity only by coral bleaching and fishing (Spalding et al. 2001). Model estimates indicate 22% of the world's coral reef ecosystems are threatened by land-based pollution, including soil erosion (Bryant et al. 1998). At a local scale, pollution can be the dominant pressure on an ecosystem. The primary stressors from land-based sources are nutrient and chemical pollution from fertilizers, herbicides, pesticides, human-derived sewage, and increased amounts of sediment from coastal development and storm water runoff (Figure 10). Other pollutants, such as heavy metals and oil, can also be prominent at specific locations. Direct impacts of pollutants include reduced recruitment, the loss of biodiversity, altered species composition (shifting from predominantly phototrophic to heterotrophic fauna), and shallower depth distribution limits (ISRS 2004).

In addition to land-based sources of pollution, chemicals and nutrients (e.g., mercury, iron, nitrogen, and phosphorous) are also introduced via atmospheric deposition following long-range transport from distant origins (e.g., African and Gobi desert dust). It is not yet known how mercury, which is transformed to biologically hazardous methyl mercury after deposition to the ocean surface, might affect corals. Iron, nitrogen, and phosphorus are critical and potentially limiting nutrients on coral reefs. The atmospheric input of iron, nitrogen, and phosphorus represents an increase in the nutrient loading of the water body, with biological consequences that cannot be ignored. For example,

too much phosphorus can lead to weak coral skeletons that increase the coral's susceptibility to storm damage (Wilkinson 1996). The primary mechanism of iron deposition is rainfall and it is the sole source of iron to coral reef ecosystems (aside from shipwrecks). In addition to chemical and nutrient deposition, atmospheric transport may also carry disease-producing organisms, such as the soil fungus *Aspergillus sydowii*, which has been thought to be introduced to coral reef ecosystems through African dust deposition (Smith et al. 1996; Kellogg and Griffin 2003).

While pollutants can occur alone, they often occur together and interact synergistically. For example, sediment runoff from land can potentially introduce toxicants and disease-producing microorganisms to coral reef ecosystems which can affect coral function and survival. Additionally, pollutants may be introduced by multiple sources as in the case of reactive nitrogen and phosphorous, which may be introduced via land-based inputs, atmospheric deposition, or upwelling. Pollutants can impair coral function and may make the corals more susceptible to disease, climate change, and the presence of invasive species. Research is needed to better understand the allowable concentrations or thresholds of pollutants and to determine the tolerance of coral reef ecosystems to pollutant concentrations (i.e., at what concentration does an effect occur).

Management actions to address water quality concerns are taken by the U.S. Environmental Protection Agency (EPA), U.S. Department of Agriculture, NOAA, and local, state, territorial, and commonwealth governments, depending on jurisdictions. Research is needed to understand how coral reef ecosystems respond to impaired water quality, and to provide managers with tools to detect, assess, and remedy negative impacts. To this end, the sources of the substances that adversely affect water quality must be identified, and relevant policies and strategies developed and validated. Monitoring of sediment, water, and coral tissue for likely pollutants (e.g., organic contaminants, trace elements, nutrients, and pathogens) in threatened or high pollutant concentration areas can alert managers to changes in pollutant inputs and impacts.

Changing attitudes and behaviors is central to any effort to reduce nonpoint sources of pollution. Thus, understanding the factors influencing individuals' attitudes, and the driving force(s) behind particular behaviors is a critical element of addressing this



Figure 10. Pollutants, such as nutrients from fertilizers, herbicides, pesticides, human-derived sewage, and increased amounts of sediment from coastal development, can have direct impacts on coral reef ecosystems, including increasing turbidity. Photo credit: Deborah Gochfeld.

issue. As addressing pollution concerns requires coordination among an array of Federal, state, territory, commonwealth, and local agencies, research on these institutional features and how data are collected should be linked to reducing the threat of pollution to coral reef ecosystems. Research indicates that knowledge alone does not beget responsible environmental behavior; however, resource managers can be more effective in targeting education and outreach activities with an understanding of how the public perceives impacts of land use and other human activities.

General research questions relevant to understanding and improving water quality in coral reef ecosystems include: What are the economic and social factors that influence the adoption of pollution control measures, the use of agricultural inputs, or perceptions of different nutrient-related best management practices (BMPs) in agricultural areas? Are some corals or coral reef ecosystems more resistant to pollution stress than others? What are the long-term implications of differential resilience on coral reef ecosystem community structure and function? How does pollution affect coral reef ecosystem resiliency to

other local and global stressors? How long do impacts caused by pollutants persist once the stressor is reduced or eliminated? How fast does change occur within coral reef ecosystems due to pollution from either chronic low-level inputs (e.g., sewage) or episodic high-level inputs (e.g., storm water runoff, rainfall, and upwelling)? What are the best measures of pollutant impacts on coral reef ecosystems? What are the best ways to reduce pollution and what are the costs and benefits of available options relative to each other and to addressing other stressors? What are the pollution impacts on compromised organisms subjected to additional stressors from both allochthonous (i.e., derived from outside the system) and natural sources? Which watersheds contribute the highest loads of contaminants, including sediment and nutrients, to coral reef ecosystems? What is a system's vulnerability to chronic versus episodic pollution? What are the relationships between coral condition and presence/input of specific and multiple contaminants and the concentrations of those contaminants? How do impacts from contaminants vary with distance from the source of those contaminants? How does increased sedimentation impact coral reproduction and larval recruitment?



Figure 11. A golf course located on the shoreline near a coral reef (Mangilao, Guam). Photo credit: Dave Burdick.

Coastal Uses

Coral reef ecosystems are being damaged — continually and in some cases irreparably — by a number of anthropogenic impacts, some of which are avoidable. Non-extractive human activities that may damage or impact coral reef ecosystems include recreational activities (e.g., boating and scuba diving), shipping, coastal development (Figure 11), weapons testing, vessel groundings, anchor damage, and marine debris accumulation. Scores of shipwrecks exist which may retain fuel, explosives, and/or other pollutants that threaten not only the condition of the reefs, but also the safety of divers. Construction, excavation, and dredging associated with new or expanding facilities (e.g., for ports, navigational channels, bridges, and underwater cables) can also cause direct and indirect damage to coral reef resources, such as sedimentation that can literally smother the corals and turbidity that decreases the amount of light available to the corals (Muller-Parker and D’Elia 1997). Military weapons testing, toxic and hazardous waste disposal, base construction and operation, unexploded ordnance, and warfare can also cause direct and indirect damage to coral reefs and are of key concern in the U.S. Pacific Islands.

Some coastal uses restrict access or prohibit all other uses, as is the case for some areas managed by U.S. military, Federal, state, territory, commonwealth, and/or

local resource management agencies. When these areas are managed as limited access sites, whether the goal is to provide security, serve as reference sites for research, or protect sensitive critical habitats, they can serve as de facto MPAs. Research is needed to understand the role of these restricted areas in managing coral reef ecosystem resources. For restricted access areas that are used in a non-sustainable manner (e.g., as ammunition ranges), the role of research is to document resource damage or loss and predict ecological, economic, and societal costs and benefits of that use.

Other coastal activities impact reefs by causing the accumulation of marine debris. Marine debris consists of not readily biodegradable trash, including lost and derelict commercial fishing nets, metals, plastics, and rubber products (Figure 12). Marine debris accumulation is considered a high-level threat by coral reef managers in the Northwestern Hawaiian Islands and the Federated States of Micronesia; and as a medium-level threat in Florida, Puerto Rico, the Main Hawaiian Islands, the Commonwealth of the Northern Mariana Islands, the U.S. Pacific Remote Insular Areas, and the Republic of Palau. Derelict commercial fishing nets can dislodge and break coral colonies and entangle marine mammals, sea turtles, fish, and seabirds. Marine debris is also a vector for exotic species introductions. Removing marine debris is an expensive and difficult task. In 2004 alone, 112 metric tons

of debris, primarily derelict fishing gear, was removed from reefs and beaches in the Northwestern Hawaiian Islands at an estimated cost of \$2.8 million. Research is needed on how to apply or develop remote sensing techniques to aid in the identification of floating debris and other materials near coral reef areas that can impact the reef.

By increasing resource use, coastal development and tourism increase the potential for recreational overuse and misuse. To better determine the appropriate levels of resource use for both existing and new areas, research is needed to identify mixed and heavy use areas where user conflict and resource damage are most likely to occur, and to quantify the effects of commercial and recreational use of these areas (e.g., loss of coral cover, biodiversity). Additionally, the drivers behind recreational misuse should be identified and used to target education and enforcement. Research needs to focus on institutional arrangements and how laws, policies, and organizational relationships influence the use, management, and protection of reef ecosystems. There has been extensive social science research on “common pool” resources and how institutional relationships can increase or decrease the effectiveness of addressing problems associated with such resources (Ostrom and Ostrom 1972; Ostrom 1988a, 1988b). Findings from these studies have documented the importance of particular institutional arrangements as drivers for conservation and management. This work also emphasizes the importance of examining how different institutions or individuals use scientific and locally-derived information within decision-making processes for natural resource management. This work should serve as the

foundation for research assessments on the institutional relationships and how they benefit or impair coral reef ecosystem management.

General questions relevant to coastal uses include: What are the impacts and associated costs and benefits of maintaining navigational access? What are the carrying capacities of different coral reef areas in a variety of coastal situations at local and regional scales? What are the ecological and economic consequences of coastal uses? What are the sources of marine debris? Can technology be developed to locate and remove debris before it gets entangled on reefs? What are the economic and social drivers for particular coastal uses (including conservation activities) that impact coral reef ecosystems? How do changing demographic and economic patterns correlate with particular stressors and the quality of reef habitats? What are the costs and benefits of different approaches to managing coastal uses?

Invasive Species

Alien species (also known as exotic, non-native, introduced, and/or non-indigenous species) are plants, animals, and microorganisms that have moved as a result of human activities from their native geographic range and habitat to a new location. Alien species are considered to be “invasive” if the alien species acts as ‘an agent of change and threatens native biological diversity’ in its new location (IUCN 2000). It is important to note that not all alien species become invasive or cause economic or ecological harm by displacing, outcompeting, or preying on native species.

Alien species may be introduced to coral reef ecosystems via vectors or pathways such as shipwrecks, ship hulls and ballast water, waterways, aquaculture systems, aquarium discards into coastal waters, marine imports, and marine debris. Recent evidence also suggests that both fungal and bacterial pathogens from terrestrial habitats could also be transferred to coral reef ecosystems (Porter 2001). Intentional and unintentional releases of invasive species have been documented worldwide and are often the focus of expensive control and eradication programs. For example, in Waikiki on the island of Oahu in the Main Hawaiian Islands, there have been 14 volunteer-led cleanups to remove approximately 85 tons of an invasive alga, gorilla ogo (*Gracilaria salicornia*), from August 2002 to February 2005 (Figure 13; Smith et al. 2004; Hunter et al. 2004). In the Atlantic, the lionfish *Pterois volitans*, a



Figure 12. NOAA diver frees an endangered Hawaiian monk seal from marine debris (Northwestern Hawaiian Islands). Photo credit: Ray Boland, NOAA Fisheries.



Figure 13. The invasive red alga, Gracilaria salicornia, washed up on Waikiki Beach after a large summer swell. This alga has become quite abundant on the reefs around Oahu since its introduction in the 1970s. This species poses a threat to the reefs in the Hawaiian Islands as it appears to outcompete many of Hawaii's native species. Photo credit: Jennifer E. Smith.

native to the Pacific, is now well established and suspected to be reproducing from North Carolina to south Florida (Figure 14; Hare and Whitfield 2003). The potential impact of lionfish on native species is unknown. To date, lionfish have not been sited south of Miami; however, should lionfish make their way to the Florida Keys, the impact to the ecosystem could be significant.

Research can contribute to reversing the trend of increasing invasive species in U.S. coastal waters by improving prevention, detection, prediction, response, and restoration. The science of invasive species is relatively new, but it is clear that prevention is easier and cheaper than eradication. Early detection tools are needed to alert managers of alien species before they become established. As few survey programs exist to monitor for alien species, by the time they are noticed, they are often well established and eradication or control is not an option. When an alien species is detected, research is needed to determine its vectors of origin, potential for future spread, and potential to become invasive. Increased understanding of species tolerances and life cycles can be applied to predict the risks associated with alien species introduction. This is especially important as new geographic areas provide suitable conditions to invasive species as a result of environmental and anthropogenic factors such as climate change, excess nutrients, and

overfishing. Predictive risk assessments on species likely to become invasive can forecast their potential ecological and socioeconomic impacts. Researchers should also develop and evaluate new strategies and technologies to prevent introductions, eradicate invasive species, and mitigate their effects. With the information from targeted research, coastal managers can make contingency plans and take coordinated actions to prevent future occurrences and establishment of invasive species and mitigate existing and future species effects.



Figure 14. The lionfish, Pterois volitans, native to the Pacific Ocean, has been found off the U.S. east coast from North Carolina to north of Miami. Photo credit: Lance Horn, NOAA's Undersea Research Program Center at the University of North Carolina Wilmington.

As alien species are primarily introduced via human activities either intentionally or unintentionally, documenting the human attitudes and perceptions towards alien species could be important research. For example, aquaria and pet stores play a fundamental role in shaping attitudes related to exotic fish. Understanding how these actors view the threat of exotic species, regulations, and potential environmental impacts is a critical step to reducing the introduction of exotic species into the environment. Similar research on sport fishermen could help reduce the threat from bait fish introductions. Research on institutional and intergroup relationships will also help ensure that managers are targeting the appropriate groups and that their message is positively received.

General research questions with relevancy to the management of invasive species include: What native species occur in each coral reef ecosystem? What is the extent and distribution of existing populations of invasive species? What are the likely vectors for introduction? What ecological factors facilitate successful competition with native species, especially for species that are known to be outcompeting native species? How have anthropogenic or natural changes facilitated the establishment of invasive populations, and can management actions mitigating these changes reduce the introduction and spread of invasive species? What are the predicted and observed ecological, social, and economic impacts of an established invasive species? What are the public's perceptions of non-native species and their impacts on coral reefs?

Climate Change

Climate change, in particular increases in temperature and carbon dioxide levels primarily from the burning of fossil fuels, threatens coral reef ecosystems through increased occurrence and severity of coral bleaching and disease events, sea level rise, and storm activity (Figure 15; Smith and Buddemeier 1992; Hoegh-Guldberg 1999). Climate change may also reduce calcification rates in reef-building organisms by lowering the pH of seawater and reducing the availability of carbonate ions (Feely et al. 2004; Kleypas et al. 2006). Reduction in calcification rates directly affects the growth of individual corals and the reef's ability to maintain itself against forces that cause reef erosion, potentially compounding the 'drowning' of reefs caused by sea level rise (Hoegh-Guldberg 1999; Schiermeier 2004; Langdon and Atkinson 2006).



Figure 15. Shoreline erosion likely due to storm activity. Photo credit: Dave Burdick.

The frequency and severity of coral bleaching events has increased over the last 25 years (Reaser et al. 2000; IPCC 2001a, b; Lackner 2003) and bleaching is considered a major threat to coral reef ecosystems (Table 3; Figures 16 and 17). Coral bleaching (the process in which a coral polyp, under environmental stress, expels its symbiotic zooxanthellae from its body, and appears whitened or "bleached") is caused by a multitude of stressors, such as increasing ocean temperatures and extended light exposure. Predictions call for even greater frequency and severity of bleaching events over the next 50 years (Reaser et al. 2000; IPCC 2001a). There is considerable evidence that global temperature, including seawater temperature, has increased substantially over the last century, in large part, to the burning of fossil fuels (Reaser et al. 2000; IPCC 2001a, b). However, the physiological mechanisms linking climate change to bleaching and the intra- and inter-species variability in bleaching responses are just beginning to be understood (LaJeunesse et al. 2003). For example, little is known about the environmental conditions and mechanisms whereby ultraviolet radiation (UV) and PAR interact with temperature increases to induce coral bleaching (Jones et al. 1998; Dunn et al. 2004). Long-term monitoring and research are needed to understand the underlying causes of coral bleaching (Hoegh-Guldberg 1999), to clarify initial and long-term impacts of coral bleaching events, and to identify factors affecting resistance and resilience to coral bleaching. Monitoring of key physical and chemical data in real- and near-real time at coral reef sites, including temperature, salinity, PAR, UV, water clarity, nutrients, and carbon dioxide, is needed to relate environmental changes with observed

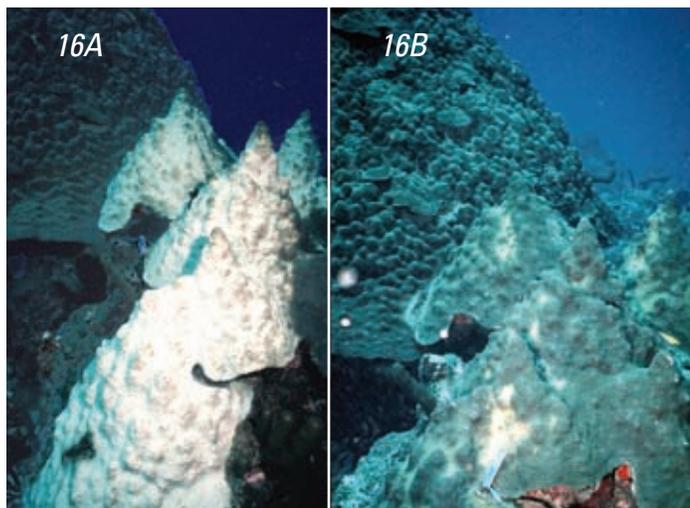


Figure 16. A bleached (A) mountainous star coral colony, *Montastraea faveolata*, photographed five months later is shown to be almost fully recovered from the bleaching event (B). Photo credit: Andy Bruckner, NOAA Fisheries.

responses (Jones et al. 2000), such as coral bleaching, algal blooms, and disease events. Research is also needed to better understand factors that might act synergistically with elevated seawater temperatures to change predicted bleaching responses. For example, high exposure to middle wave UV (or UVB) might lower the seawater temperature thresholds for predicted bleaching events or increased water turbulence might increase predicted seawater thresholds (Dunn et al. 2004).

Long-term records of local sea surface temperatures from coral cores and other paleoclimatic sources may be used to place more recent records of bleaching events and changes in coral communities within a longer temporal perspective. The effects of longer temporal variability, including the Pacific Decadal Oscillation/Variability, the El Niño Southern Oscillation, and other important climate oscillations, should be examined for their role in climate change. Other research should delineate and validate biological impacts of decreased pH on calcifying and non-calcifying organisms.

Given that managing climate change is beyond the scope of coral reef managers, effective management of coral reef ecosystems affected by climate change requires a better understanding of coral reef ecosystem resiliency. Coral reef ecosystem resiliency is defined as “the return of a coral reef ecosystem to a state in which living, reef-building corals play a prominent functional role, after this role has been disrupted by a stress or perturbation” (UNEP 1999, p. 2). One management strategy is to mitigate stress

and damage caused by local stressors to improve reef condition and thus, make the ecosystem less vulnerable to local, regional, or global bleaching events. Management actions before, during, and after bleaching events might also reduce local stressors, thus helping to facilitate recovery. For example, fisheries management actions to promote herbivores that reduce algal populations at overfished sites; boating restrictions to reduce anchor damage; and shoreline setbacks, greenbelts, and exclusion zones in areas vulnerable to waves, sea level rise, or flooding may reduce nutrient and pollutant loads to reefs and may be beneficial in reducing stressors when corals are recovering from a bleaching event.

The following questions target climate change research with significant relevance to management issues: How much of the variability in bleaching observed within and among species (and within and among coral reefs) is explained by environmental patchiness (in temperature, light, water motion) compared to phenotypic and genotypic variability in corals and their symbiotic algae? What are the relative contributions of global, regional, and local stressors and their interactions to particular ecosystem responses? What are the most important factors influencing recovery after coral bleaching events? Does the addition of human impacts and the fragmentation of coral reef habitats (affecting gene flow) undermine coral reef ecosystem resiliency and make them more susceptible to coral bleaching? What is the relationship between coral bleaching and non-temperature related stressors such as light and pollutants? How does climate



Figure 17. (A) A bleached colony of brain coral, *Diploria labyrinthiformis*, during the 2005 Caribbean bleaching event, and (B) a healthy colony of brain coral (Big Point, Lee Stocking Island, Bahamas). Photo credit: Deborah Gochfeld.

change affect coral exposure to these stressors? How will warming, sea level rise, changing circulation patterns, and increased dissolved carbon dioxide in the ocean affect the way coral reef ecosystems look and function over the next 50 to 100 years? What is the relationship between the decline of coral reef ecosystems caused by bleaching and the condition of reef-dependent fisheries? How have corals responded to climate and carbon dioxide variability in the past? Can methods be developed to detect past coral bleaching events and to better understand how corals respond to changes in temperature and temperature variability? What can be done at a local/regional levels to increase the chances of recovery after a bleaching event? What effect will decreased calcification rates have on ecosystem structure and function?

Extreme Events

Extreme events include abiotic (e.g., volcanic activity, lava flows, hurricanes, floods, droughts, sea level rises, tsunamis, and oil spills) and biotic events (e.g., population die-offs, coral predator outbreaks, and disease). These events can produce profound ecosystem changes both directly and indirectly. For example, extreme abiotic events may remove or cause the mortality of corals (Figure 18), thus, indirectly making the substrate available for the colonization of macroalgae, bioeroding sponges, and other encrusting invertebrates that inhibit the recruitment of stony corals. Research is needed to understand and predict changes resulting from extreme events versus natural variability.



Figure 18. An abraded and overturned elkhorn coral, *Acropora palmata*, was detached during a storm. Photo credit: Andy Bruckner, NOAA Fisheries.

Physical impacts of extreme events can persist for extended periods; for example, strong winds and waves from hurricanes and storms can directly impact reefs by toppling corals, resuspending sediment, and increasing turbidity. Storms, floods, and droughts also affect coral reef ecosystems by changing inputs of freshwater and associated nutrient, sediment, and chemical pollutants. Hurricane and severe storm forecasting capabilities have vastly improved in recent years, but coastal communities are still unsure how to best reduce and mitigate the damage that these storms produce. To help fill this need, researchers should forecast expected coral reef ecosystem changes resulting from extreme abiotic events. Researchers also need to better understand how extreme events influence human use and protection of coral reef ecosystems. For example, if a hurricane damages or destroys particular reef areas on which tourist and fishing activities depend, do the impacts of these activities shift to other reefs, thereby negatively impacting coral areas not directly damaged by the storm? Understanding the use patterns and decision-making processes of stakeholders can help managers proactively protect critical coral reef areas.

Understanding and forecasting how population outbreaks and die-offs affect coral reef ecosystems, and how those events affect change if other stressors are present, are other critical management needs. The long-spined black sea urchin (*Diadema antillarum*) die-off in the 1980s and COTS (*Acanthaster planci*) outbreaks are examples of unanticipated biotic events with far-reaching impacts on coral reef ecosystems (Figures 19 and 20). In 1983, researchers documented an unprecedented Caribbean-wide die-off of the urchin *Diadema antillarum* (Lessios et al. 1984; Lessios 1995). The *Diadema* die-off resulted in a reduction in grazing pressure and has been implicated in the increase in fleshy algal cover on coral reefs where herbivorous fishes had been overfished. The occurrences of COTS outbreaks have been documented when environmental conditions favor larval settlement and have resulted in the sudden occurrence of large numbers of COTS on extensive coral reef areas [note: the Great Barrier Reef Marine Park Authority defines active outbreaks as areas with more than 30 adult COTS per hectare (Engelhardt 1997; Fraser et al. 2000)]. While COTS outbreaks are a natural occurrence, increased nutrients and exploitation of natural predators may favor larval and juvenile COTS.



Figures 19. A crown-of-thorns starfish, *Acanthaster planci*, outbreak along a reef track in Guam. Photo credit: Dave Burdick.



Figure 20. A crown-of-thorns starfish, *Acanthaster planci*, shown feeding on a soft coral, *Sinularia polydactyle* (Piti Bomb Holes, Guam). Photo credit: Deborah Gochfeld.

Disease in corals and associated organisms has dramatically increased in frequency and distribution over the last decade, contributing to unprecedented decreases in live coral and altering the function and productivity of coral reef ecosystems (Figure 21). In the Caribbean, white-band disease has been implicated as the principal cause of mass mortalities of elkhorn coral (*Acropora palmata*) and staghorn coral (*A. cervicornis*), with losses of 80 to 95% accompanied by an ecological phase shift from a coral-dominated to algal-dominated reef (Aronson and Precht 2001). Some evidence suggests that stress may increase susceptibility to disease. There is also a possible relationship between disease and climate change, as pathogenic organisms are often most virulent

at increased seawater temperatures. The potential relationship between anthropogenic stressors and disease suggests that the emergence of disease as a major factor causing high levels of coral mortality is relatively new, and management strategies targeted towards reductions in other stressors (e.g., land-based pollutants) may reduce the likelihood of disease outbreaks. Thus, research is needed to examine the underlying cause(s) of disease in coral reef ecosystems, the mechanisms of infection, and the relationship between disease and stress. In addition, research is needed on the basic biology and physiology of corals to serve as a baseline for coral health and disease investigations and to better distinguish between disease and natural changes (e.g., growth and reproduction).

Beginning in March 2000, the Coral Disease and Health Consortium was established through an interagency partnership between NOAA, EPA, and the U.S. Department of the Interior (DOI), with involvement by over 50 domestic and international partner institutions, to provide a comprehensive approach to understand and address the effects of natural and anthropogenic stressors on corals. The *Coral Disease and Health: A National Research Plan* identifies three major research priorities: 1) standardize terminology, monitoring protocols, collection techniques, reporting standards, and laboratory protocols to provide a consistent, integrated body of scientific information; 2) define baseline measurements of coral health and vitality, examine occurrences of disease, and determine the causes and effects of declines in coral health; and 3) investigate the effects of anthropogenic, environmental, and climatic stressors on coral health (NOAA 2003a). Additional priorities were the dissemination of technical information and practical diagnostic tools to improve the ability of managers and scientists to evaluate, track, predict, and manage coral diseases; and improved multidisciplinary collaborations and cross-disciplinary training for scientists and managers.

The following management-relevant questions target extreme events in coral reef ecosystems: To what extent and by what mechanism is disease affected by other factors, such as temperature, light, sediment, nutrients, and pollutants (and in what combinations)? How many different diseases significantly affect coral reef ecosystems and what are their etiologies? Is there variability in susceptibility and resistance to disease observed within and among species (and within and among reefs)? If so, what are the roles played by environmental patchiness (in temperature, light, water motion) and phenotypic or

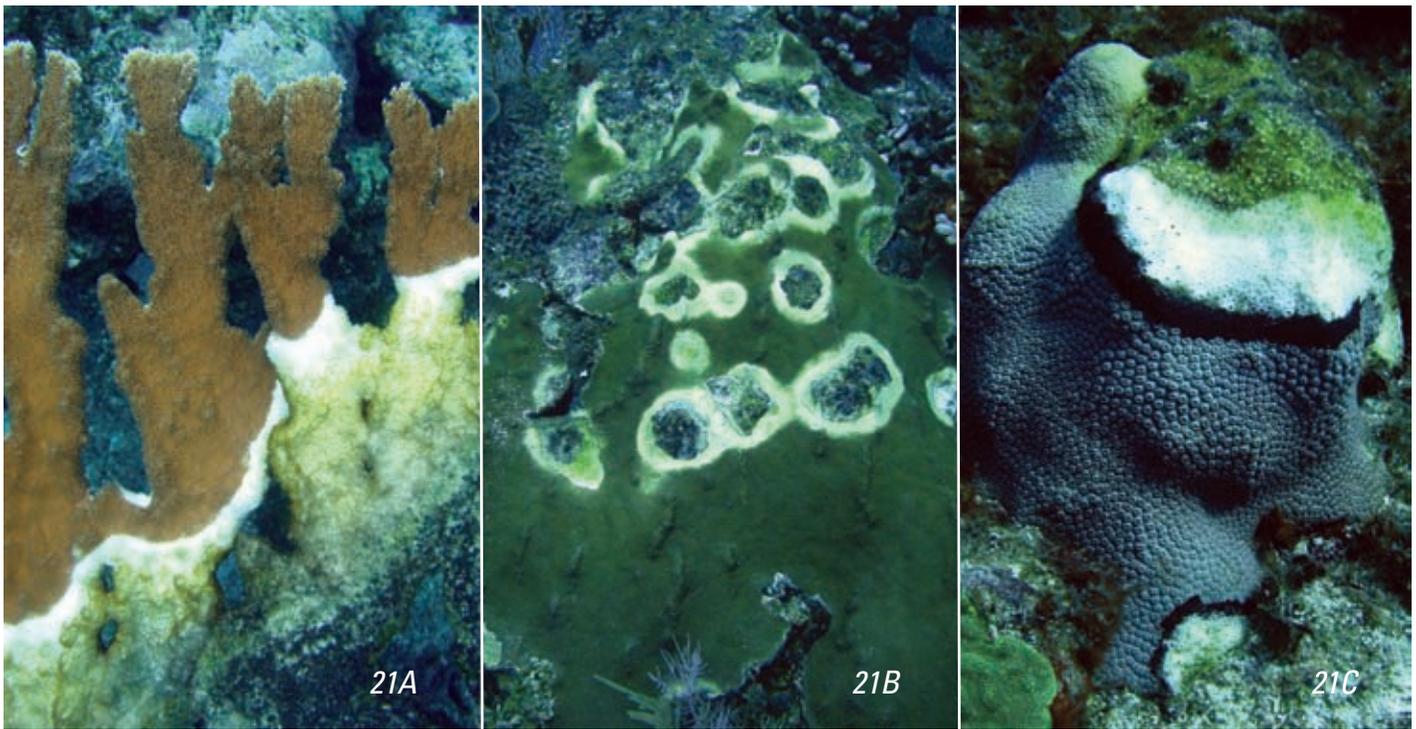


Figure 21. Images of diseased corals. (A) A colony of elkhorn coral, *Acropora palmata*, with white band disease (Pajaro Reef, Mona Island, Puerto Rico, 2003). (B) A colony of mountainous star coral, *Montastraea faveolata*, with yellow band disease (Carmelita Reef, Mona Island, Puerto Rico, 2006). (C) A colony of mountainous star coral with black band disease (Mujeres Wall, Mona Island, Puerto Rico, 2006). Photo credit: Andy Bruckner, NOAA Fisheries.

genotypic variability (related to coral defense mechanisms and immune systems)? What are the most important factors influencing recovery after coral disease epizootics (i.e., an outbreak of disease affecting many animals of one kind at the same time)? What is the relationship between the loss of live coral and the condition of reef-dependent fisheries? What is the relationship between extreme events and the use of different reef resources? Are local agencies structured to address the management and information needs associated with extreme events? How do changing quantities of runoff, the timing of extreme events, and the nature and extent of resulting physical damages affect coral reef ecosystems?

TECHNOLOGY SUPPORTING RESEARCH AND MANAGEMENT

Essential components of this Research Plan are the technologies, tools, and techniques used to carry out the research and management objectives. Every day, scientists employ numerous technologies to better understand the world. Many of these technologies are essential to a scientist's ability to view, measure, assess, and evaluate the environment and yet, Federal planning and investment in technology research and development has remained unchanged for the past decade (USCNS 2001; USCOP 2004). It is the purpose of this section to

identify technology research and development priorities for improving the monitoring, research, and management of coral reef ecosystems.



Figure 22. Scuba diver cleans marine growth off of NOAA's Aquarius, an underwater laboratory located in 64 ft. of water at the base of a coral reef in the Florida Keys National Marine Sanctuary. Aquarius provides a special diving capability, called saturation diving, which allows scientists to work out on the reef up to nine hours a day, compared to one hour if they had to work from the surface. Photo credit: NOAA's Undersea Research Program Center at the University of North Carolina Wilmington.

Although many technologies are currently available, improvements are needed. Research and management of coral reef ecosystems could be aided by a national effort to develop low cost technologies for use by resource managers and scientists (Crosby et al. 1996); to disseminate existing engineering and oceanographic concepts or models; and to develop new tools and techniques.



Figure 23. An advanced scuba diver. This diver is carrying four cylinders: two in front (filled with oxygen and mixed gases) and two on his back (filled with air or mixed gases). Advanced diving techniques allow divers to extend the depth limit and bottom time per dive to significantly increase the undersea areas where self-contained wet-diving scientists can make first hand observations, take fine measurements, and conduct experiments. NOAA and its university partners are working to establish diving procedures to extend the safe diving depth limit for scientists from 130 ft. to 300 ft. Photo credit: Doug Kesling, NOAA's Undersea Research Program Center at the University of North Carolina Wilmington.

Priorities for research and development include technologies that:

- improve in situ observations, monitoring, and measuring of coral reef condition and change including: developing low cost chemical and biological sensors that provide resource managers with an “early warning” on declines in environmental condition; improving rapid assessment techniques; developing habitat characterization and sea bed classification schemes, which incorporate management-relevant criteria; advancing diving techniques to enable scientists to spend more time underwater (Figures 22 and 23), including the next generation of underwater laboratories (Figure 22); developing remotely operated observatories and supporting technologies (e.g., in situ sensors, satellite imagery) to allow for observations of remote coral reefs, including monitoring remote coral reefs for unauthorized fishing; assessing populations and behavior using non-traditional means (e.g., stereo video and passive acoustics technologies) by developing new non-destructive, fishery-independent approaches; developing alternative methods to erecting seawalls to mitigate coastline changes; developing algorithms to interpret acoustic and optical remote sensing data for improving the accuracy (>90%) of large island maps; and developing expert computer systems that analyze collected data and provide the results in a format understandable to decision-makers.
- improve the understanding of factors influencing coral reef ecosystem dynamics and change, including developing predictive models or forecasts of ecosystem condition that incorporate management-relevant criteria, and ecosystem response to natural events (e.g., storms, floods) or anthropogenic impacts (e.g., eutrophication, sewage discharges).
- avoid and minimize impacts to coral reef ecosystems by providing resource managers with guidance concerning BMPs and developing new fishing technologies and gear.
- minimize adverse impacts of aquaculture to the environment and wild stocks by developing criteria for aquaculture facility site-selection, permissible discharges, and environmental impact assessments (NOAA 1998).

- improve the ability to grow and reproduce coral reef ecosystem species in captivity to reduce pressure from the aquarium industry on natural stocks and to be used for habitat restoration, including improving the understanding of natural inducers for spawning and larval settlement.
- develop biotechnological techniques to improve the understanding of complex biochemical systems.
- minimize environmental impacts during the research and development of new marine-derived drugs and commercial products.
- improve the management of coral reef ecosystems by using networks of MPAs and establishing drivers for particular human uses of reef ecosystems, including ensuring that incentives exist for environmentally-sustainable alternatives.
- develop coral restoration techniques.

Marine Protected Areas

A MPA is an area of the marine environment that has been reserved by Federal, state, territorial, commonwealth, tribal, or local laws and/or regulations to provide lasting protection for part or all of the natural and cultural resources therein (E.O. 13158, May 26, 2000). A MPA can have various levels of protection, from no-take reserves to multiple-use areas that may allow fishing or other uses and extractive activities, and may include multiple zones with different protection levels across this spectrum. There are many examples of MPAs in the U.S. (Figure 24), including national parks, national marine sanctuaries (Figure 25), national wildlife refuges (NWR), fisheries



Figure 24. A marine protected area (Tumon Bay, Guam). Photo credit: Dave Burdick.



Figure 25. Glassy sweepers, *Pempheris schomburgkii*, and a stand of elkhorn coral, *Acropora palmata* (Florida Keys). Photo credit: NOAA Florida Keys National Marine Sanctuary.

closures, habitat areas of particular concern, and state parks. MPAs with common purposes or contributions to common goals can function as networks to protect specific species and their linked habitats across geographic scales and conditions.

MPAs and MPA networks are considered essential components of marine ecosystem management (NRC 2001). On May 26, 2000, President William Jefferson Clinton issued E.O. 13158: Marine Protected Areas, which set forth policies to strengthen the management, protection, and conservation of existing MPAs and establish new or expanded MPAs. E.O. 13158 also directed NOAA and DOI to work with other Federal agencies and consult with states, territories, commonwealths, tribes, and the public to develop a scientifically-based, comprehensive national system of MPAs. In September 2006, NOAA, in concert with DOI and various stakeholders, released a draft framework in the Federal Register that outlines guidance to develop the national system of marine protected areas (MPAs) in the U.S. (NOAA 2006a).

While the use of MPAs and MPA networks as resource management tools has grown significantly in recent decades, there is still substantial scientific investigation needed to better understand the appropriate design, size, number, and siting characteristics that ensure their effective use. Research focusing on the development of criteria for MPA and MPA network design, including the size, location, connectivity among MPAs, and their ecological and socioeconomic impacts, is needed. Growing scientific and observational evidence

indicates that no-take marine reserves may increase the health and abundance of corals, reef fishes, and other reef-associated species within these sites. However, targeted research is required to better understand the effect of no-take reserves on resources, particularly outside of reserve boundaries (e.g., spillover effects and enhanced reproduction output [Sladek Nowlis and Friedlander 2005]). MPAs do not protect all species equally; for example, animals that move long distances relative to the size of the MPA receive less protection. Nevertheless, mounting scientific evidence shows that MPAs can increase coral reef fish and invertebrate abundance and biomass because protection from fishing allows animals to live longer and grow larger. This has been hypothesized to increase the export of larvae and coral reef ecosystem resilience, although few research projects or monitoring programs address these issues directly. Additionally, there is a need to oceanographically characterize MPAs to enable calculation of larval drift and to better understand migration pathways for better site-selection of MPAs. Research should also be conducted to determine the effects of long-term de facto MPAs (e.g., marine waters within military zones, security zones, harbors, and airports) on surrounding fished areas.

The human dimension of MPAs is critical to the success of planning, development, management, and monitoring of MPAs and MPA networks. Historically, most research on MPAs has focused on natural science; however, recent studies have shown that social factors, as much as or more than biological or physical factors, determine the success of a MPA. In establishing and managing MPAs, managers need to understand how the areas may impact the people who use them, and how users, in turn, impact those areas and non-MPA areas. Social science research is needed to fill information gaps and help MPA programs identify and consider important issues, such as public attitudes and perceptions, relationships between and among uses and users of the marine environment, impacts of MPAs on the character of communities, and direct and indirect economic impacts of MPAs over time.

General research questions related to the effective application of MPAs and MPA networks as management tools of coral reef ecosystems include: How do location, size, and oceanographic

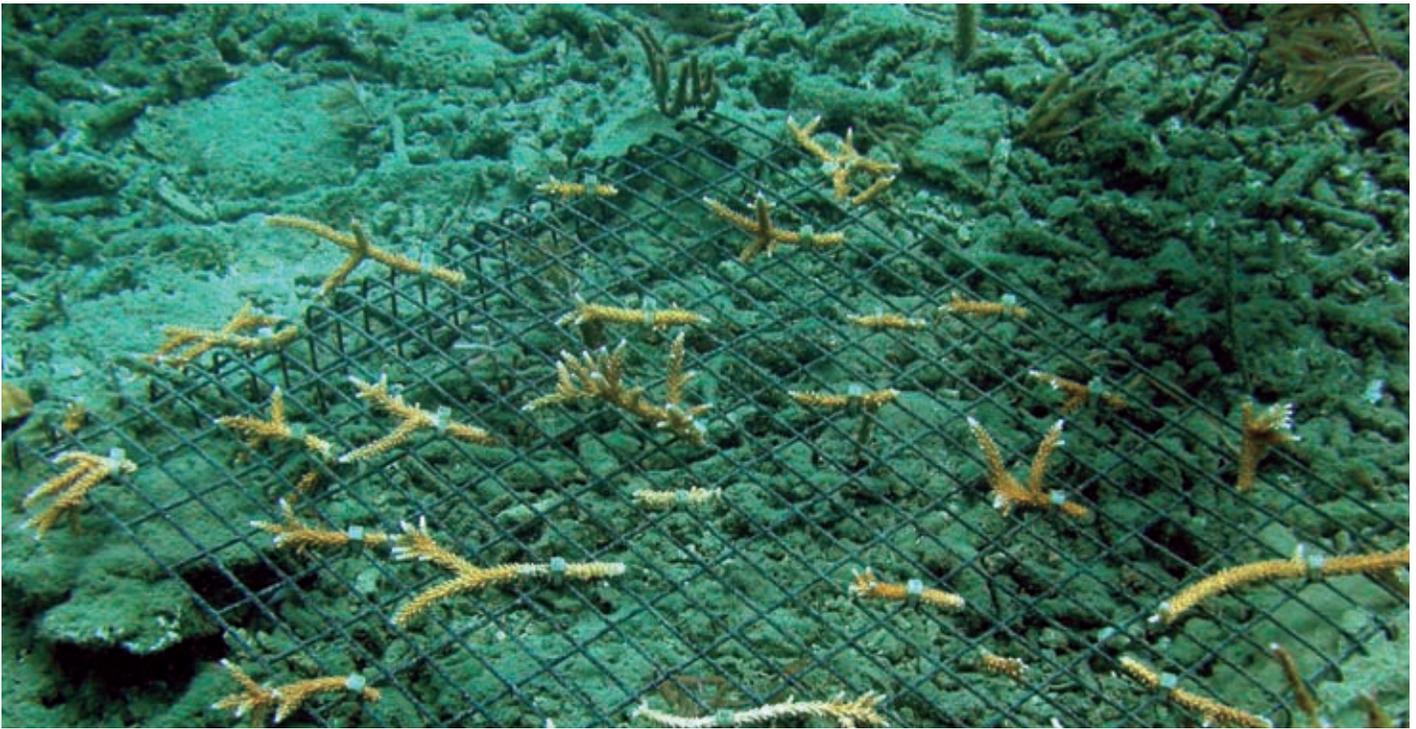
processes influence MPA function and efficiency in terms of meeting both biophysical and socio-cultural objectives? Where and what level of protection is needed for MPAs to enhance the resilience of coral reef ecosystems, improve fish stocks, and manage risk associated with multiple stressors? What factors affect and enhance the recovery of exploited species within no-take reserves and how long does it take to see a response for economically and ecologically important species? What are the spillover effects (e.g., export of larvae and fish) from reserves to MPAs and MPA networks? What are the effects of MPAs and MPA networks on commercially or recreationally harvested species inside and outside MPA boundaries? What socioeconomic factors enhance support for and compliance with rules and regulations associated with MPAs by fishers and/or other stakeholders? What factors associated with the processes to design and establish MPAs have the most significant effect on acceptance of MPAs by the public? What impediments exist to adding more MPAs? What ecosystem impacts and benefits are provided by different MPA access restrictions? How can fish spawning aggregations be used in the design of MPAs and MPA networks? How can local knowledge and social capital be utilized to improve MPA acceptance and long-term effectiveness?

Habitat Restoration

The dramatic and widespread loss and alteration of coral reefs have generated discussion about replacing what was lost or accelerating the rate of recovery



Figure 26. A diver prepares to reattach an elkhorn coral fragment, *Acropora palmata*, in response to the Fortuna Reefer grounding (Mona Island, Puerto Rico, 1997). Photo credit: Erik Zobrist, NOAA Restoration Center.



*Figure 27. Staghorn coral fragments, *Acropora cervicornis*, are attached to a wire frame as part of a restoration effort at the M/T Margara grounding site off Guayanilla Bay, Puerto Rico. This staghorn coral nursery shows rapid growth after one month as evidenced by the new branches. Photo credit: Andy Bruckner, NOAA Fisheries.*

from damage. Restoration is defined as the “return of an ecosystem to a close approximation of its condition prior to disturbance” (NRC 1992, p.11). Most projects aim to restore the ecosystem to its condition prior to the disturbance, but in many cases recovery converges on a community that is different from its pre-disturbance state (Aronson and Swanson 1997).

The science behind coral reef ecosystem restoration is still in its infancy. The few restoration efforts that have occurred to date have been relatively small-scale responses to physical damage from vessel groundings, anchorings, dredging, and other coastal development activities. These emergency restoration efforts have included righting and reattachment of displaced and broken coral (Figure 26), and the removal of coral rubble. Some of these restoration efforts have used underwater cements and other substrates in combination with creative engineering to repair structural fractures (e.g., obliterated spurs and holes caused by large propeller excavations) and to stabilize rubble. To date, very few restoration efforts have addressed the living component of the coral reef ecosystem, with the exception of transplanting fragments (Figure 27) or cementing dislodged corals back in place.

One example of a resource injury documentation and small-scale restoration process is in the Florida Keys National Marine Sanctuary (FKNMS). Vessel groundings in the FKNMS have damaged over 30,000 acres and pose a major threat to coral reefs and seagrass beds (FKNMS 1997). Depending on the extent of the injury, a vessel grounding in the FKNMS can initiate a sequence of events that includes injury assessment, emergency triage (i.e., emergency righting and reattachment of displaced or broken corals, and stabilization of the substrate), possible litigation between the natural resource trustee agency and the responsible party or parties responsible for the damage, and a detailed damage assessment and restoration project (Precht et al. 2003). NOAA has a strong legal mandate through the National Marine Sanctuaries Act (16 U.S.C.1443) and the Natural Resource Damage Assessments rule (15 C.F.R. 990) to recover losses of natural resources and their services from the responsible party, including compensation to restore damaged resources and compensation for lost services from the time that the damages occurred until the resources have recovered based on an established economic process to calculate damages. This includes collection of a monetary damage claim to restore the damaged resources as closely as possible to their pre-injury condition (primary restoration), and to replace the services lost over time from

the injury (compensatory restoration) (Shutler et al. 2006). It does not include conducting research on how to restore coral reef ecosystems. In 1994, \$3.76 million was paid as a settlement for destruction of 345 m² of reef area due to a ship grounding. The recovered funds were applied to primary and compensatory restoration, including monitoring of the restoration site (NOAA 1999).

Prior to undertaking restoration, it is important to verify that the factors responsible for the original loss are not still present; the area of interest has the capacity to be restored; and clear restoration project goals, a measurable endpoint, and parameters for measuring achievement have been identified. Additionally, the project design may need to be altered during the restoration process in light of new information or problems (i.e., adaptive management). It is important to note that despite localized efforts to curtail degradation (Patterson et al. 2002; Szmant 2002; Wilkinson 2002; Turgeon et al. 2002; Gardner et al. 2003; Lang 2003; Pandolfi et al. 2005), in general, coral reef loss is ongoing unabated. This loss suggests a broader consideration of global processes (such as the effects of expanding human demands on the environment) might be necessary in coral reef restoration efforts.

Hypothesis-driven research is needed to evaluate and improve coral reef ecosystem restoration efforts including criteria development for determining when restoration is a viable option and assessing the socioeconomic costs and benefits of restoration and its alternatives; the development and comparative evaluation of restoration techniques, including the examination of both unimpacted controls and impacted/unrestored controls; the experimental testing of the efficacy of different restoration options; and quantifiable measurements of restoration project success. Long-term monitoring programs to measure the success of a restoration project should incorporate an experimental design and be based on hypothesis-driven questions. The development of models that predict resource recovery with and without restoration may also guide decisions on where and when to intervene.

Social science research related to habitat restoration and protection should investigate the factors driving support for or opposition to such efforts. This could

include an examination of different institutional factors driving both the use and protection of coral reef ecosystems. Study of local attitudes and perceptions regarding habitat conservation efforts could also be important to the long-term success of restoration and conservation efforts.

Management-relevant questions pertaining to habitat restoration include: What do monitoring results from existing restoration projects, compared to results from undamaged coral reefs, tell us about community processes that are important for recovery, such as coral reproductive biology, coral recruitment, algal growth, links between coral health/habitat provision and fish populations, resistance to perturbations, and coral reef ecosystem resilience? What techniques, if any, significantly enhance the rate and trajectory of recovery to predamaged condition or some other defined restoration goal? How do physical oceanographic processes, both large-scale (km) and small-scale (m), facilitate or hinder recovery and restoration efforts? Are instituted management actions preventing vessels from striking previously damaged areas? Do existing policies and institutional arrangements lead to desired restoration outcomes? What institutional/socioeconomic factors impede the implementation of restoration efforts?

TRANSFERRING SCIENCE AND TECHNOLOGY INTO OPERATIONS

Coral reef ecosystems will benefit from the research conducted and supported by NOAA and other organizations only if that research is transferred into operations by management authorities in a timely manner. NOAA relies on research results to develop management actions based on sound science to fulfill its statutory and regulatory responsibilities. Thus, data should be analyzed and disseminated to resource managers quickly. Too often, data collection is completed, but it is years before the information is shared, and by then the information is outdated.

End-to-end research planning outlines the path for the transfer of new technologies, research results, and advances in observation systems into improved operational capabilities. This transition is achieved through close collaboration between researchers and service delivery professionals at all phases of the research and development process. Frequent exchange between managers and researchers will ensure that the direction

of research is adjusted to address solutions to management problems.

As indicated in *NOAA's Five-year Research Plan* (p. 8):

“One tool for enabling the transition of research to operational use is the testbed. Testbeds provide the research community a setting to work directly with NOAA's operational elements through established testing and evaluation protocols with clearly defined goals and decision points for cost-effective and rapid transition of new research and technologies into routine operations. With the goal of accelerating infusion of technology and research results into operations, testbeds provide the opportunity to address the following:

- System design studies for the global observing system network.
- Assessing scientific breakthroughs and new techniques to identify advanced analysis techniques, numerical forecast models and methods, observational systems, and climate-water-weather linkages having potential for significantly improving forecasts.
- Using advanced statistical and numerical weather prediction model output (especially model ensemble information) and stimulating further model enhancements.
- Refining computer-based models, products, and observations in a quasi-operational information technology environment subject to metrics that mandate good scientific performance while meeting ease-of-use, reliability, and operational criteria.
- Developing enhanced verification capabilities.
- Exploring societal impacts resulting from improved products and services.”

Transferring science and technology into operations includes developing methods for managers to conduct social impact analyses; evaluating alternative management options; and developing information technology to support management decisions, such as data visualization techniques and geographic information systems (GIS). Social science research analyzing the use and evaluation of science and technology is also critical to management efforts and should include assessing the appropriate delivery mechanisms for technical information.

OUTREACH AND EDUCATION: TRANSLATING RESEARCH, IMPROVING MANAGEMENT

Outreach and education are processes used to increase public awareness, appreciation, knowledge, and understanding about coral reef issues in order to promote informed decision-making and increase stakeholder support in reef conservation. Strategic outreach is a critical and underutilized component of effective management, and is an important step in the science-to-management linkage. Just as scientists and managers should collaborate to develop research that supports the information needs of managers, outreach specialists can help identify and achieve tenable management solutions supported by the public.

Socioeconomic research can also elucidate impacts to coral reef ecosystems by providing an understanding of human motivations, which is critical information for policymakers, managers, and outreach specialists. Accordingly, socioeconomic research works hand-in-hand with outreach efforts to inform managers and policymakers of probable responses to management strategies and policy measures. Outreach and socioeconomic studies can also determine mid-course if the public is responding as anticipated to a management measure or if further outreach and feedback mechanisms are needed. In this sense, outreach activities depend on social science research examining multi-stakeholder processes and the institutional arrangements necessary to successfully manage coral reef ecosystems.

Goals of integrating research, management, and outreach to improve effectiveness:

- Promote public awareness of the status and importance of reefs, and foster a stewardship ethic.
 - Translate scientific research into information about the condition of coral reefs and the rationale for management decisions that the public can access and use.
 - Improve effectiveness and responsiveness of management through information-sharing and two-way dialogues that promote agency understanding of public values related to coral reef ecosystems, and how and why stakeholders use coral reefs.
 - Build public support for management initiatives.
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Figure 28. Youth learn about sea stars in a hands-on education program in the Bahamas. Photo credit: Staff Photographer, Perry Institute of Marine Science.

Management effectiveness can be directly proportional to public support for a given initiative. For example, a MPA is unlikely to be successful if commercial and recreational resource users do not support or understand the underlying need for the MPA. Accordingly, management initiatives benefit from the broad support of the range of coral reef ecosystem users. Outreach activities should be designed to encourage this broad support and involvement, and to solicit feedback. For outreach to be most effective, the information needs and motivations of stakeholders should be considered at all stages of the research-to-management process, from program design to implementation to performance measurement. Social science research should focus on characterizing the social, cultural, economic, and institutional environments linked to particular reef systems to allow for the development of outreach initiatives targeting specific public concerns and perceptions related to reef management.

Effective planning and coordination of national, regional, and local outreach initiatives are also imperative. Outreach

plans should consider the initial and future receptiveness to conservation goals by competing interest groups, and then develop locally- and culturally-appropriate programs that work with communities to facilitate the long-term success of resource management. Outreach activities should stem from and be tailored to an understanding of the motivations and needs of those impacted by management programs. This end-to-end integration of research, management, and outreach may decrease the need for enforcement and restoration activities, and encourage improved stakeholder behavior and participation in the management process.

Wherever possible, full integration of outreach and management strategies should be encouraged and supported by effective research. This integration is guided by the need for increased translation of scientific findings into initiatives that build public support for management goals. Outreach activities should work in tandem with research and management to cause behavioral changes through science-based information.

Established and well-documented social science tools include focus groups, opinion polling, baseline and comparative surveys of public values and awareness, as well as participatory research and planning and citizen advisory groups. NOAA's use of polling and survey work is somewhat constrained, and applying these techniques requires training in social science methods, as well as sound information on the human, social, and economic environments in which management activities are occurring. Therefore, research is needed to define additional ways with which to measure outreach activities and the impact of outreach on management effectiveness.

Examples of outreach activities include encouraging sustainable behavior through skills-building workshops and training programs with constituents; providing access and orientation to current research findings and data through information transfer tools like NOAA's Coral Reef Information System; developing and distributing educational materials and displays; fostering community involvement in conservation and restoration projects; and hosting two-way discussions with stakeholders to improve mutual understanding of resource needs and management goals. Social marketing initiatives, which use traditional marketing methods of public communication to promote sustainable behavior, have also proven quite effective. Marketing expertise can help outreach specialists and

managers develop information materials that the public can recognize. Public service announcements on radio and television, billboards, materials placed in hotels and on flights into coral reef areas represent potential options for communicating with the public.

Emphasis should be placed on encouraging effective two-way communication and information-sharing between managers and various stakeholder groups. Successful projects will support local management-to-outreach integration through effective planning and implementation, and should involve key stakeholders throughout the process as appropriate. Constituents are more likely to respond favorably to management and enforcement if they understand, have been able to anticipate, and can continue to be involved with conservation programs, becoming active hands and resources for change rather than being isolated through non-inclusive management processes.

Formal and informal education initiatives are also encouraged where appropriate. Youth education is increasingly recognized as critical to building lifelong environmental literacy and stewardship and as a precursor to a diverse workforce for future generations (Figures 28 and 29; USCOP 2004). Developing partnerships with schools and educational and community organizations can maximize limited educational resources and encourage stewardship throughout the community through service learning projects and other initiatives involving parents and others in the process of student learning. Educational programs should focus on translating the latest research into activities that help students understand the living and evolving nature of science and the need for scientists from diverse backgrounds. Finally, training for educators in the use of coral reef science and education materials is critical to ensuring the effectiveness of education programs. Educators involved with even one-time professional development workshops are many times more likely to use materials and encourage student awareness and stewardship than those who are simply handed materials without hands-on orientation (Fortner and Corney 2002).



Figure 29. Georgetown Police Youth Summer Camp provides the opportunity for local youth to learn about the sea and its creatures through the use of a touch tank (Bahamas). Photo credit: Staff Photographer, Perry Institute of Marine Science.